TECHNOLOGY OF LIGNITIC COALS

In Two Parts–Part 1: Summary of Industrial Development Possibilities; European Technology on Lignitic Coals; Occurrence and Properties; Lignite Mining in North Dakota; Preparation; Storage and Transportation; Appendix–Statistics and Costs of Lignite in North Dakota

By Bureau of Mines staff, Grand Forks, N. Dak., and Washington, D. C.

* * * * * * * * * * **Information Circular 7691**

UNITED STATES DEPARTMENT OF THE INTERIOR
Douglas McKay, Secretary
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FOREWORD

Since its creation by the Congress in 1910, the Bureau of Mines has fostered prudent exploitation of our mineral and mineral-fuel resources. Even though the United States has abundant reserves of solid fuels, sufficient to last many centuries with wise use of present reserves, it is recognized that development of our lower rank fuels in the vast untapped reserves of the North Central States will greatly enhance our mineral wealth.

Lignite as a source of fuel and chemical materials has long been regarded as an important asset to the Nation's economy. As the reserves of the higher rank coals of the Appalachian region are eventually depleted, large quantities of lower rank coals will be required to maintain our position of leadership in the industrial world. In view of this, the Bureau of Mines has been conducting investigations to develop more efficient methods of utilizing our vast reserves of lignitic coals. One notable accomplishment in this direction is the construction of a large Texas power plant, in which it is planned to employ lignite char as fuel for power generation.

This char manufacturing process with its accompanying valuable tars is the outgrowth of a process developed by the Bureau of Mines at its Denver Station. In 1951, construction of the Bureau's Charles R. Robertson Lignite Laboratory was completed at Grand Forks, N. Dak. It is anticipated that the major lignite projects of the Bureau will be conducted at this laboratory in cooperation with industry and the various Government agencies.

This report is composed of two parts. Part 1 covers the technology of European lignitic coal, statistics on production and costs of North Dakota lignitic coals, their occurrence and properties, mining, preparation, storage, and transportation; part 2 covers the utilization of lignite. Owing to the broad field discussed, it was necessary that contributions of a number of Bureau authors be assembled and integrated to facilitate the final product. A major portion of the work emanated from the Bureau's lignite laboratory at Grand Forks, N. Dak., under the guidance and authorship of Robert McMurtrie, chief of the Lignite Branch of that station, and under the general supervison of J. Daniel Lankford, chief, Fuels Technology Division, Region V, Minneapolis, Minn. Significant contributions were made by Walter H. Oppelt, Robert C. Ellman, Edward F. Golob, Gordon H. Gronhovd, Jerome J. Hoeppner, Jr., Theodore W. Kamps, Jr., Wayne R. Kube, and Alfred Traverse.

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TECHNOLOGY OF LIGNITIC COALS

Part 1 of Two Parts

by

Bureau of Mines staff, Grand Forks, N. Dak., and Washington, D. C.

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1. SUMMARY OF INDUSTRIAL DEVELOPMENT POSSIBILITIES

As a part of its overall wealth in fuel resources, the United States possesses large reserves of coal of lignite rank. According to recent estimates of the Federal Geological Survey (3, 5),[1] the assured lignite reserves of this country amount in total to over 463 billion tons, equivalent to 24 percent of our total national coal reserve on a tonnage basis and 15 percent on a heating-value basis.

Distribution and relative amounts of United States coal and lignite reserves are indicated in figure 1. By far the largest proportion of our lignite reserves, over 95 percent, is found in North Central States, principally in North Dakota, South Dakota, and Montana, in the vast coal-bearing structural grouping designated as the Fort Union formation. Of the remaining United States reserves, all but a fraction of 1 percent are found in a series of relatively scattered deposits in Texas.

Because of this Nation's extensive overall fuel-resource wealth, the large reserves of lignite have, up to the present, been comparatively little utilized. The Texas lignite deposits have for many years been in severe direct competition as an energy source with large local supplies of cheap natural gas. After reaching a maximum of over 1,000,000 tons per year in the early 1920's, production in that area has until recently followed a continuous downward trend.

In the North Central States, on the other hand, lignite production has expanded to meet the principal fuel requirements of an area of 100,000 square miles. Annual production in recent years has been over 3,000,000 tons. As yet, however, this output reflects only the demands of a primarily agricultural region for domestic and minor industrial heat and power. There has been no major industrial growth or raw-materials processing development distinct from local agricultural requirements.

As the coal lowest in rank and heating value (details of classification in sec. 3, p. 43), lignite must be mined cheaply if it is to be competitive with other coals in cost per unit fuel value, at the minesite. The average heating value (about 6,700 B.t.u. per lb. as mined) is only half that of a typical bituminous coal. Mining conditions are favorable in the lignite fields of the North Central States. Extensive reserves in this area lie at shallow depths and can be recovered at low cost by strip mining. Cost of lignite at the minesite is slightly over $2 per ton, or about 15 cents per million B.t.u.; therefore, at this time lignite is one of our cheapest fuels.

It is primarily the promise of these extensive, cheaply recoverable reserves that has encouraged current thinking with regard to large-scale industrial utilization of the vast north central lignite deposits. Present information on total surface-recoverable reserves is not complete. Nevertheless, the available data indicate clearly that

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1/ Underlined numbers in parentheses refer to citations in the bibliography at the end of this section.

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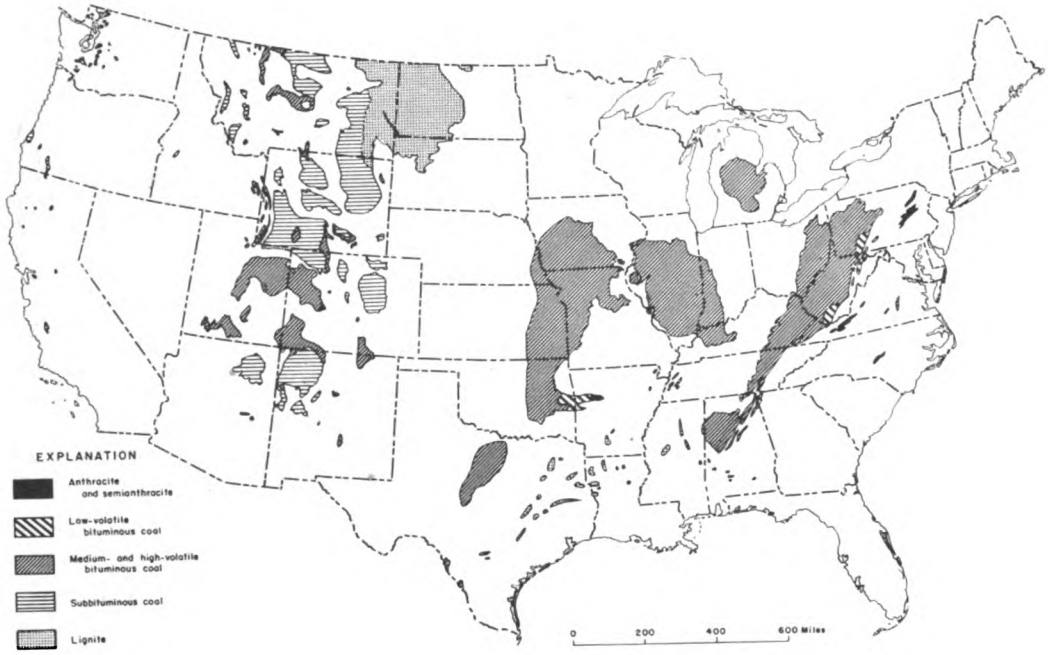
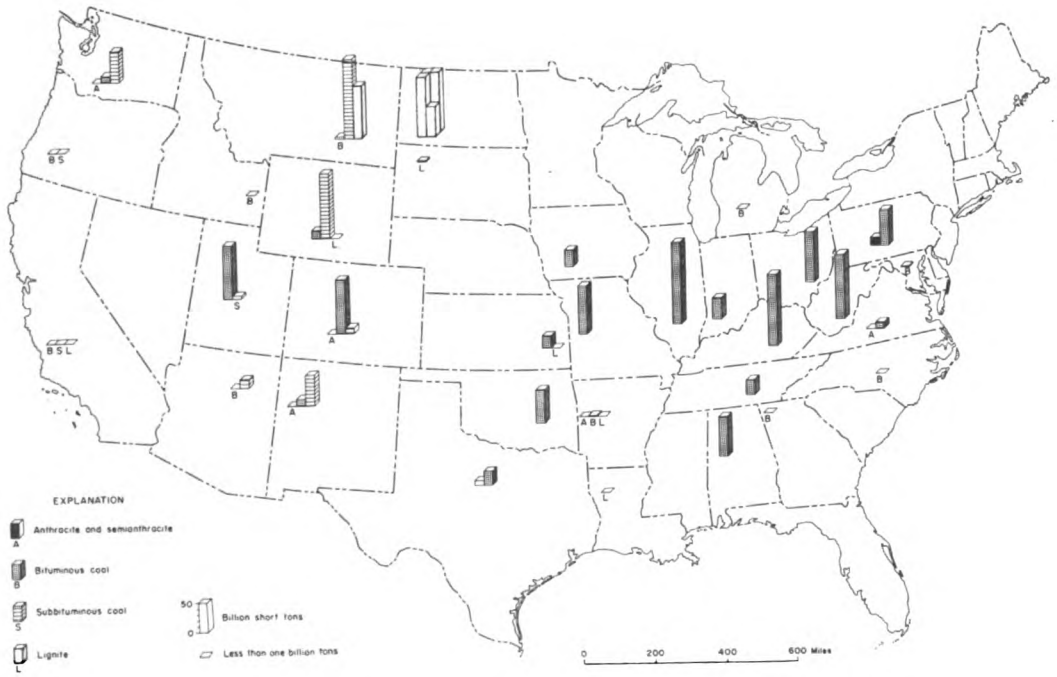


Coal fields of the United States.



Estimated coal reserves of the United States, January 1, 1953.

Figure 1. - Distribution of United States coal resources.

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lignite reserves of the North Central region that can be recovered by low-cost surface mining are far more extensive than comparable reserves in any other coal region of this country and unquestionably extend into billions of tons.

For a number of years, Gulf coast and Midcontinent natural gas at the point of production has provided this country's cheapest fuel reserve, and industrial users primarily interested in cheap fuel and cheap power have been attracted to these areas in large numbers. More recently, increased high-value use for natural gas through large-scale nationwide pipeline distribution has resulted in a steady upward price trend. At present, it seems probable that, as this trend continues, the large low-cost lignite reserves of the North Central States will soon become the Nation's lowest cost major fuel reserve.

Recently, in view of this evident trend and inability to get long-term contracts for natural gas at a favorable rate, a Texas company in the heart of the natural-gas region has turned to development of local deposits of lignite to assure a long-term cheap fuel supply. In this case, according to present plans, the net fuel cost of lignite will be reduced by credit for recovery of byproduct chemicals, using new low-cost carbonization techniques developed at the Denver laboratories of the Federal Bureau of Mines (22). The detailed significance of this development will be considered later. In general, average mining costs are higher, but byproduct recovery by carbonization is more promising for the Texas deposits than for the larger lignite reserves of the North Central States. By thorough prospecting, the Texas development interests have been able to secure a 50-year fuel reserve for their large 350,000-kw. power plant, a total of about 150,000,000 tons; however, at least half of this reserve will have to be mined by underground methods.

Industrial Fuel Use

In considering the possible directions for developing the very large low-cost lignite reserves of the North Central States, the first and most obvious possibilities are those offered by use of fuel to provide industrial heat and power. At present direct recovery of fuel energy by combustion continues to provide by far the largest coal market.

In present industrial practice lignite is burned with its as-mined moisture content, averaging 36 percent by weight as mined. The common modern method of firing is by spreader stoker. Pulverized firing has also been demonstrated and seems likely to be used in large new installations because of mechanical limitations on acceptable size of spreader-stoker units. In present conventional pulverized-firing practice, lignite is partly dried in the pulverizers by preheated primary air, and the moisture removed passes on into the furnace.

In general, modern industrial combustion experience has demonstrated that, with equipment and firing methods now in use, lignite can be burned at heat-release rates and efficiencies nearly on a level with those for higher rank coals. Boiler efficiency, expressed on the conventional basis of gross heating value, will necessarily be about 5 percent less than normal maximum efficiencies for other fuels, owing to heat requirement for moisture evaporation. Slightly more combustion space and tube surface are required for operation at maximum efficiency, because of lower flame temperatures achieved in combustion of high-moisture fuel.

The lowest costs for combustion or other use of lignite will evidently be obtained by utilization at or near the minesite. The effect of transportation costs on price of solid fuels is very severe, particularly in areas like that surrounding the north central United States lignite deposits, which are not served or approached by water-route transportation. It is not economically feasible to ship a solid fuel, particularly a low-rank fuel, for long distances even though it is very cheap in its own area.

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For example, railroad freight charges for shipping as-mined industrial lignite from mines in Mercer County, N. Dak., to consuming centers in the eastern part of that State, or 280 to 300 miles, are about $2.20 per ton, more than doubling the cost of the fuel as delivered at these points.

Availability of Industrial Raw Materials Other Than Fuel

New industrial plants with a primary need and requirement for cheap fuel, and coming into the lignite-producing region primarily on that basis, would undoubtedly be located near a mining development with locally assured and prospected reserves adequate for long-term needs. In addition to fuel, large and dependable supplies of water are normally essential. The principal dependable water supply in the north central lignite-producing area is the Missouri River, with an average annual flow of 14,350,000 acre-feet (12.8 billion gallons per day). Flow in the smaller streams is, in general, unreliable and erratic, both from month to month and from year to year. A recent detailed study by Malcolm Pirnie Engineers (16), has indicated, however, that adequate water supplies for large-scale operations, requiring over 14 million gallons per day, could be provided in nearly all sections if total plant investment were large enough to justify the cost of fairly elaborate reservoir development.

The principal large-scale industrial power consumers with fundamental requirement of cheap power include the electrometallurgical industries, primarily aluminum, magnesium, copper, zinc, electric furnace steel, and ferroalloys; the electrolytic alkali industries based on sodium chloride; producers of phosphorus, calcium carbide, and graphite, and producers of fused-alumina, silicon carbide, and other refractories.

In most instances raw materials other than fuel required for these various processes are not found in or close to the north central lignite-producing area in economically recoverable grades or quantities. In oil-well drilling, salt beds containing over 99 percent sodium chloride have been discovered at depths of 7,000 to 8,000 ft. Local availability of limestone is limited. Large commercial-grade deposits of low-silica bauxite for aluminum production are found in the United States only in Arkansas - although work in progress by the Bureau of Mines on development of a process for recovery of alumina from regional deposits of anorthosite (calcium aluminum silicate) may offer possibilities.

Power costs are of fundamental importance to these industries, but it is evident that transportation of raw material to processing location and of products to suitable markets is also significant. In most instances, the cost advantage of lignite for fuel use will have to be sufficient to attract raw materials from other areas for processing before such development occurs.

The lack of water-born transportation represents a handicap. Development of navigability of the upper Missouri River to the lignite-producing area could influence the picture, particularly with regard to aluminum production. Although much of the river will become navigable with completion of the Missouri Basin flood-control dams, up to the present no provision has been made for bypassing of the dams by river traffic.

Regional hydroelectric power from the Missouri Basin multipurpose dams will not be available, according to present plans, at a cost level competitive with lignite-generated power for large-scale use, or low enough in cost to attract major power-consuming industrial processors. Present cost assigned to Garrison Dam hydropower is 5.5 mills per kw.-hr. Lignite at the present industrial price of $2 per ton should permit a power cost as low as 3.55 mills, for very large fixed-load generation and consumption, on the basis of recent studies for 240,000- to 800,000-kw. power plants by Vern E. Alden Co., power-plant engineers (8).

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Long-Distance Transportation of Fuel or Power

In a few instances large-scale transportation of fuel or power for industrial utilization at some distance from the lignite deposits may be economically promising. This would apply in providing fuel or power to existing concentrations of industry or to raw-materials development possibilities where a clear advantage exists for local processing of the raw materials.

In the North Central States, the main possibilities for new industrial markets away from the lignite-producing area lie to the east and southeast, where no significant supplies of native fuels are available over considerable distances. The present consuming area for lignite extends about 300 miles from the lignite deposits in these two directions. The extent of this area is clearcut and extends to the limit where fuel cost of lignite is approximately the same as the cost of eastern coals delivered from the northern Lake ports, or, toward the southeast, against coal barged up the Mississippi River, principally from Illinois and Kentucky. To the north and west of the lignite deposits, lack of population and availability of immediate supplies of coals, which are also recoverable at relatively low cost, have prevented development of markets for lignite.

The two important consuming areas that may be within economic reach of the North Central region lignite deposits through development of cheaper transportation methods are the Minneapolis-St. Paul industrial area and the northern Minnesota iron-range country. In the iron-range country, large amounts of electric power will be required in the near future for processing the low-grade taconite ore deposits soon to undergo increasing utilization. Present delivered cost of fuels now used in these two areas is slightly over twice the minesite cost of lignite, or about 32 cents per million B.t.u. Railroad transportation cost for delivering lignite to these areas is about $3.50 per ton, so that delivered cost of lignite would be about 2.75 x minesite cost.

The main opportunities for substantial reduction in transportation costs for fuel or power appear to lie in new developments in pipeline transportation of fuel or in long-distance transmission of power generated at the minesite. Both of these methods show promise where demand is large enough, although neither pipeline transportation of solid fuels nor power transmission at voltages up to 500,000 volts, which promise the greatest economy for long distances, have been commercially developed as yet.

Analysis of data now available indicates, however, that these methods offer the possibility of providing transportation costs from the lignite area to Minneapolis-St. Paul or to northeastern Minnesota, for very large scale demand, which may be as low as $1.60 per ton, or 1.4 mills per kw.-hr. (detailed information in section 6). Each of these transportation methods involves large investment cost, and fixed demand on a very large scale together with assurance of the long-term fuel-cost and power-demand picture would be necessary to justify their use. Demand of at least 500,000 kw. or higher in a specific concentrated market area would be required.

Total existing demand in the Minneapolis-St. Paul area is about 500,000 kw. Eventual power demand in the iron-range country for processing taconite has recently been estimated at 600,000 kw. minimum (14). Additional markets for lignite beyond the power market could be developed in both areas if large supplies were made available cheaply. In the iron-range country sintering and agglomeration of ore fines provide an existing market. Partial reduction of nonmagnetic taconite to permit separation, together with possible developments in partial or complete ore reduction, represent future possibilities.

In general, pipeline transportation or long-distance power transmission could also be used to lower delivered cost or equivalent cost for competitive coals. In

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the two consuming areas under consideration, however, competitive coals benefit at the present time from low-cost water-route transportation.

Chemical Processing

For most large-scale chemical-processing operations involving the production of bulk chemical products or liquid fuels, lignite has no specific major advantage over other hydrocarbon source materials. Its use in this connection, like direct industrial fuel use, will be primarily encouraged and determined by availability at low cost. Although numerous processing problems remain unresolved in their detail at this time, the general outlines and possibilities for such chemical processing are reasonably clear.

Carbonization

Carbonization or destructive distillation is probably the simplest method for recovering bulk chemical products from coals. Such thermal processing yields a liquid fraction that contains the main products of interest for chemical use; a low-B.t.u. gas; and a large solid residue, which, for the low-rank coals, has value in general only as fuel.

Among the United States deposits of lignite that are adequate for commercial exploitation on large scale, the maximum yields of total liquid products by carbonization are of the order of 16 gallons per ton, or 6.7 percent by weight. Yields in this range are obtained from the Texas lignite deposits now being developed for fuel use and byproduct chemical recovery (9, 21). On the basis of present evidence, representative yields of total liquid products from North Central States lignites are substantially lower, averaging about half this figure.

Because of the high proportion of residue having only fuel value, the recovery of chemical products from low-rank coals by carbonization must necessarily be associated with a large-scale fuel market. The potential of carbonization in a given area is therefore closely related to the existence or possibilities for development of large markets for fuel.

The high-temperature carbonization of coking coals is carried out on a very large scale in this country, about 115,000,000 tons per year, primarily to produce metallurgical coke for blast-furnace use. The liquid products of high-temperature carbonization, which are the major source of today's coal chemicals, are recovered from coke ovens as secondary-value products. Sale of these byproducts for other than fuel use is not essential, although in most instances the main products of chemical value are recovered under normal market conditions.

Coal carbonization at lower temperatures than those used in coke-oven practice produces larger quantities of liquid products. Maximum yields are obtained at temperatures of about 900° F., versus the 1,800° to 2,200° F. temperatures attained in coke ovens. In carbonizing the noncoking coals, where the primary aim is to develop value of the liquid products for chemical use, attention has centered on processing at low temperatures. In addition to the larger yields of liquid products obtained, a further incentive for low-temperature processing is found in the requirement that the residual solid material of char retain enough volatile matter to represent an acceptable fuel.

In the past, low-temperature carbonization has been economically successful only under specialized conditions, primarily where the char produced has been able to find a premium market as smokeless low-volatile domestic fuel. If the char is to be used as boiler-furnace fuel, the entire burden of cost of the carbonization operation,

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plus any net cost advantage, must be derived from credit obtained for liquid products. The low-B.t.u. gas produced has only conventional industrial fuel value and is, in most instances, consumed to provide the heat required for the carbonization process.

Although coal tar is complex in nature, most of the individual chemical products for which there are bulk markets under present-day conditions are relatively simple in structure. In general, such markets exist only for the lower molecular weight members of the several chemical series that are present.

The liquid products from high-temperature carbonization are highly aromatic. Commercially recovered bulk chemicals from high-temperature tar and light oil include large quantities of simple aromatic compounds, benzene, toluene, xylenes, naphthalene; the aromatic tar acids, phenol, cresols, xylenols; and, in smaller amounts, the tar bases, primarily pyridine. A number of higher molecular weight constituents are also recovered in relatively small quantities for specialized uses in the synthesis of dyestuffs, pharmaceuticals, and other organic specialties. In addition, larger complex fractions find various nonfuel uses; that is, crude creosote oil for wood preservative use and tar-distillation residue for road tar, bituminous coatings, etc. These relatively low value crude fractions represent by far the largest volume products recovered from that portion of coke-oven-tar production which is fully processed and not burned as fuel.

Low-temperature tar characteristically contains high yields of tar acids and low yields of simple aromatic compounds. Naphthalene, which may constitute up to 10 percent of the total weight of high-temperature tar, is not present in tar recovered from low-temperature processing. Yields of benzene, toluene, and xylene are limited or nonexistent. Tar bases are comparable in total quantity with those from high-temperature tar, but relatively little pyridine is present (23). The large neutral-oil fraction amounts to over 40 percent of low-temperature lignite tar and consists of about 60 percent paraffins and unsaturates and 40 percent aromatics. The aromatics have potential value but are largely higher molecular weight alkyl-substituted benzenes and naphthalenes, which are difficult to separate. When recovered from petroleum fractions, these higher boiling aromatics are sold mainly as mixtures for solvent use (27) at prices substantially lower than those for benzene, toluene, and xylene (30). Under existing conditions, the neutral-oil fraction of low-temperature tar can be considered to have approximately the value of similar petroleum fractions for direct use as liquid fuel or as feedstock for conventional petroleum processing. Data on naphthene content and suitability for further aromatization have not yet been developed.

At present, the demonstrated value of low-temperature tar for chemical or nonfuel use, through recovery of individual bulk chemicals, is limited very largely to the tar acids. Total tar-acid yields are high, up to 20 percent of the total tar or higher (22), where yields from high-temperature tar are only about 2 percent. However, only a limited proportion, perhaps 25 percent, of the tar acids from low-temperature carbonization are in what is termed the "salable" range, up to the xylenols in molecular weight. Present bulk markets in the manufacture of plastics and resins, synthetic fibers, and agricultural chemicals will not accept the higher molecular weight products at this time. Consequently, a good deal of effort has been devoted, in connection with developing low-temperature carbonization, to attempts to crack the high-molecular-weight tar acids to the low-molecular-weight products in principal demand.

Further credits to low-temperature tar, which may be higher than fuel value, include use of various crude fractions to produce pitch residue, road tar, bituminous coatings, wood-preservative oil, etc. It is doubtful, however, that credits for these relatively low value products can justify in themselves the use and cost of the carbonization process.

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The maximum yields of liquid products from carbonization of lignites are obtained from deposits in Texas, Arkansas, and California. Of these various deposits, only certain of those in Texas are large enough to be commercially exploitable for large-scale fuel use and byproduct chemical recovery. The high tar yields from the Arkansas and Texas deposits are associated with their relatively high content of waxy and resinous materials, spores, leaf cuticles, etc., as discussed in section 3. Yields of liquid products from carbonization of the characteristically woody lignites of the North Central States are only about half the yields from the Texas deposits and one-fourth of the yields from certain Arkansas deposits (26). Data on even crude characterization of low-temperature tar from different lignite areas are quite limited. Available evidence indicates, however, that the percentage of the important tar-acid fraction in low-temperature tar derived from the woody lignites of the North Central States may be appreciably higher than the percentage of this fraction in tar from carbonization of lignites with higher wax and resin content (18).

The future potential of low-temperature carbonization of noncoking coals depends on proving out tar value and on reducing carbonization cost to the minimum level. A marked advance in carbonization methods has been achieved by the recent successful development of fluidized carbonization techniques by the Denver laboratories of the Federal Bureau of Mines (22). Such techniques offer the possibility of achieving very high carbonization capacities and consequent low cost per unit of coal processed.

Low-temperature carbonization on a scale large enough to make tar processing profitable must necessarily be associated with a large fuel market. Before such carbonization can be regarded as promising commercially, credits for recovered tar must be proved and demonstrated sufficient to pay for the processing operation and to provide a net cost advantage.

Gasification and Hydrogenation

Two principal methods are available that permit the essentially complete conversion of solid hydrocarbons to liquid products having potential markets as chemicals or as liquid fuels. One is the direct addition of hydrogen under pressure, involving splitting and partial breakdown of the coal complex into lower molecular weight products. The second is complete breakdown of the original hydrocarbon to carbon monoxide and hydrogen, by partial combustion or gasification, followed by reintegration of these materials into the desired end products.

Either of these processing methods can be used to convert coal essentially completely to relatively high value products. Their use in a given area, therefore, in contrast to low-temperature carbonization, is not tied to the existence or simultaneous development of a large-scale market for solid fuel residue.

Synthesis of liquid and gaseous fuels

The largest eventual use of these coal-processing methods will presumably be found in the synthesis of liquid fuels. The relative position of the two processing methods for liquid-fuels synthesis is not finally defined at this time, although many observers believe that the final advantage for this specific purpose is likely to lie with the gas-synthesis process (4). At the present state of processing knowledge, the two processes remain competitive, and the Bureau of Mines, under its synthetic fuels investigation program, is continuing research and development work on both.

The prospective eventual coal market for synthesis of liquid fuels is extremely large. In this country, the consumption of petroleum has recently reached a level with present coal production and consumption on a total thermal value basis. Thermal

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efficiency of conversion of coal to liquid fuels, by known methods of processing, is at best about 50 to 55 percent.

At present, however, synthesis of liquid fuels from coal is not economically feasible under conditions existing in this country and could not be made economically feasible by the most hopeful extensions of present processing technology. Petroleum is too abundant and its cost is too low at this time to leave an adequate margin for manufacture from the cheapest coals (10, 17). The present cost situation with respect to synthesis of high-heating-value gas from coal, as a substitute for natural gas, is similar. A recent detailed cost study on the synthesis of high-B.t.u. gas from coal, by means of gasification under pressure followed by methane synthesis, indicates a cost of 55 cents per 1,000 cubic feet, based on use of 13,000-B.t.u. coal at $4 per ton (1).

Under foreseeable circumstances, the timing of synthetic liquid fuel developments will be almost entirely a function of the rate of discovery of natural petroleum relative to rate of consumption. Proved petroleum reserves in this country are adequate for about 14 years at the present rate of petroleum consumption. Although the rate of consumption of petroleum has increased very rapidly in recent years, rate of discovery of new reserves has kept pace, and in the last decade each year has seen new net additions to the proved reserves (2).

Production of synthetic liquid fuels will become promising when the oil-discovery rate takes a downturn or fails to pace consumption. Since petroleum reserves cannot be accurately predicted and can be proved only by drilling, there is no general agreement as to when this development is likely to occur. Estimates of ultimate United States reserves range up to 1,000 billion barrels, enough for 500 years at the present rate of consumption (25, p. 193). Conservative estimates of ultimate reserves are of the order of 110 billion barrels, which would leave only 40 billion barrels, or a 20-year supply, yet to be discovered (24, p. 166). This conservative total does not include a further 65 billion barrels estimated to be eventually recoverable from existing oil fields when justified by higher price levels in conjunction with improved secondary-recovery methods (10).

When discovery of new reserves declines and price levels increase, petroleum production will be supplemented initially by reworking older fields, probably accompanied by the recovery of liquid hydrocarbons from oil shale (7). Imports can also be used to supplement production in this country under normal conditions. A longer time lag and a substantial price increase will presumably be required before large-scale production of liquid fuels from coal becomes economically feasible.

It should be noted that when synthesis of liquid fuels from coal does develop, as a result of declining petroleum reserves, the synthetic products will necessarily cost more, in relation to cost of solid fuels, than liquid fuels do today. As a result, the incentive for direct use of solid fuels, wherever possible, will be more pronounced than it is at present.

When the production of liquid fuels from coal approaches the range of economic practicality in this country, one of the first and most promising sources of raw material for such processing will be provided by the very large cheaply minable low-rank coal reserves of the North Central States, with by far the largest potential being represented by the billions of tons of surface-recoverable lignite in the Fort Union formation. In this instance the raw materials problems that exist with respect to industrial development based on direct fuel use are largely avoided.

According to present evidence, the economics of synthetic liquid fuels production from lignites is approximately the same as that of other coals, if the cost of lignite

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as mined and delivered to the hydrogenation plant is about one-half that of bituminous coal. Total yields from complete hydrogenation to liquid fuel products are lower than for high-rank coals, based on moisture and mineral-matter-free coal substances, as discussed in section 4, part 2 (15, 28).

In gas-synthesis processing, only the primary gasification step depends fundamentally on characteristics of the original hydrocarbon source material. Present data show that lignite is at least as satisfactory as other coals for oxygen-steam gasification by entrained fine-particle methods, on which much of the recent gasification research in this country has been concentrated (6, 13, 29). This gasification technique was selected for development under the Bureau of Mines synthetic liquid fuels program because of its applicability to all types and ranks of coal, coking and noncoking.

Recent reappraisal of gasification techniques has led to the conclusion that lump-fuel fixed-bed gasification may provide the lowest synthesis-gas production costs, when this technique can be used, because of better heat economy and lower consumption of oxygen. Renewed interest and attention in development work to fixed-bed gasification now appears probable. For this type of processing, the noncoking lowest rank coals have a clearcut advantage, since coals that are even weakly coking cannot be used directly and must be preprocessed by partial oxidation or other means.

Gas-compression costs for pressure gas-synthesis operations are minimized by carrying out the initial gasification step under pressure, and present gasification development work for production of synthesis gas is nearly universally directed toward pressure operation at 300 to 450 p.s.i. At these pressures, fixed-bed gasification yields substantial quantities of methane. This methane must be removed or converted to carbon monoxide and hydrogen for liquid-fuels synthesis but represents a net advantage for the specific synthesis of methane, to provide a concentrated high-heating-value gaseous fuel. To supplement solid and liquid fuels, high-B.t.u. gas may also be produced on large scale from solid fuels for pipeline distribution to metropolitan centers. Necessarily this high-B.t.u. gas will have a higher base cost, in relation to cost of solid fuels, than natural gas does today and will find a more restircted and specialized market.

The synthesis of liquid fuels from coal by hydrogenation or gas synthesis offers numerous possibilities for recovery of byproducts with potential value for chemical use. Value of many of these byproducts, at present price levels, would be substantially above their equivalent value as liquid fuel. The large-scale processing of solid fuels for liquid-fuel production will represent a huge and costly enterprise. Replacement of one-fourth of the present petroleum production, or about 1,400,000 barrels per day, by liquid-fuels synthesis from coal would require a plant investment of the order of 20 billion dollars under known technology. If their production were encouraged, chemical byproducts from a synthetic fuels industry on this scale would far exceed the requirements for any foreseeable chemical markets. Thus in long-term planning of a synthetic fuels industry geared to meet eventual requirements, the logical assumption has been that the potential chemical byproducts could not be marketed and would have to be suppressed or converted and diverted to use as fuels.

In recent years these concepts have been altered to some extent by the very rapid growth of the chemical industry and the demand for bulk chemical materials. It now appears probable that synthetic liquid fuels production from coal may get its initial start as a byproduct operation in processing carried out primarily for chemical synthesis, on whatever scale the chemical market can support (11).

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Synthesis of Bulk Chemicals

Hydrogenation. - In general, hydrogenation of coal under mild conditions produces high yields of the entire series of aromatic chemical compounds normally obtained as products of coal carbonization - benzene, phenol, nitrogen bases, and their higher molecular weight alkyl-substituted derivatives and homologues. These aromatic chemicals are converted by more severe hydrogenation to largely aliphatic compounds primarily useful as liquid fuels.

With the rapid growth of the chemical industry, the demand for many aromatic chemicals, particularly benzene, toluene, phenol, and naphthalene, has already exceeded, or is expected shortly to outstrip, the capacity of conventional coke-oven sources to produce them. Recovery from petroleum fractions is now used to a considerable extent to supplement coke-oven supplies of aromatics. However, supply of the excess demand by coal hydrogenation may eventually prove more advantageous, on the basis of present development work (11). It is evident that coal hydrogenation offers the additional possibility of providing aromatic chemicals for integrated chemical development in areas where these important primary materials would not otherwise be available.

In general, detailed characterization of hydrogenation products from various coals and optimum processing conditions for high yields of chemical products have been only incompletely studied, by bench-scale evaluation or otherwise. Most assay studies to date have been concerned primarily with maximum yields of liquid products on severe hydrogenation as a criterion of promise for liquid-fuels production, and detailed characterization and evaluation of constituents have not been attempted. L. L. Hirst and others (20) present data on characterization of products from continuous liquid-phase hydrogenation of various rank coals, including two North Central lignites, at 420° to 460° C. and 3,200 to 4,600 p.s.i., and at residence times permitting nearly complete conversion to liquid products. Under these operating conditions, concentrations of neutral aromatic constituents in the product oil and molecular weight range of these products were closely similar for all ranks of coal examined. Yields of phenolic constituents were slightly higher for the low-rank coals. Total neutral aromatics from lignite were about 22 percent of the dry ash-free coal and total phenolics 14 percent.

As pointed out by Donath (12), wide alteration in final aromatic content and molecular weight distribution can be effected by secondary processing operations. Table 1 shows yields and types of products from a typical 30,000-barrel per day coal-hydrogenation plant, according to Donath. Only the salable phenolics and only the aromatic chemical products, as listed, which have bulk chemical markets are recovered. Other constituents are processed to provide maximum yields of these desired products, with inevitable additional quantities of hydrocarbons suitable only for use as liquid fuels.

Gas Synthesis. - Chemical production from gas-synthesis processes is well established commercially for the synthesis of ammonia and of methanol. These two products can be synthesized specifically. Synthesis of higher molecular weight oxygenated compounds by carbon monoxide-hydrogen synthesis inevitably yields a complex conglomerate of alcohols and other oxygenated products, for which bulk markets on a scale justifying use of this synthesis do not yet exist in this country. At present, components in particular demand - primarily acetone, acetic acid, isopropyl, and butyl alcohols - can be derived more specifically from petroleum fractions and fermentation sources.

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TABLE 1. - Chemical and fuels production from coal-hydrogenation plant of 30,000 barrels per day capacity (12)

	Pounds per day	Barrels per day	Weight-percent of total product
Phenol	157,400	428	1.9
o-Cresol	17,600	48	.2
m-p-Cresol	192,000	530	2.4
Xylenols	136,000	374	1.6
Benzene		2,210	8.2
Toluene		3,770	13.9
Xylenes		4,190	15.4
Mixed aromatics		1,780	6.8
Ethyl benzene		750	2.8
Naphthalene	316,000	790	3.7
		14,870	56.9
LPG		7,300	16.4
Motor gasoline		5,260	15.6
Aviation gasoline		3,660	11.1
		16,220	43.1
Total		31,090	100.0

Ammonium sulfate . . . . 450 tons per day
Sulfuric acid . . . . . 89 tons per day

Ammonia synthesis represents a chemical synthesis operation for which an independent local market can perhaps be developed in the North Central States to supply local agricultural requirements for nitrogen fertilizers. The maximum plant size that the area could support for fertilizer production specifically has been estimated at 200 tons ammonia per day. Production from a plant of this size would be three times the 1951 consumption of nitrogen fertilizers by Montana, North Dakota, South Dakota, Wyoming, Nebraska, and Minnesota (19). The total consumption of lignite by such a plant, if this fuel raw material were confirmed as the cheapest source of synthesis hydrogen, would be about 240,000 tons per year. Larger ammonia requirements could result from requirements of an integrated chemical industry for ammonia, nitric acid, and other products.

In general, use of lignite for chemical processing will be determined in terms both of the basic cost of this raw material and of the relative state of advancement of technological and processing knowledge. Specifically, the principal bulk products available for large-scale integrated chemical development would be aromatic chemicals from hydrogenation; ammonia, nitric acid, methanol, and formaldehyde from gas synthesis; and, potentially, higher alcohols and oxygenated acyclic compounds. These primary products would evidently meet the basic needs for primary materials of the largest bulk producers of chemical hydrocarbon-derivative end products; including most plastics, elastomers, synthetic fibers, detergents, and bulk agricultural chemicals.

The economic evaluation of individual possibilities for production of primary bulk materials is influenced and complicated by the probable eventual need and requirement for integrated development and the necessity for evaluation on this basis. However, production of primary bulk chemicals might be carried out, in its initial stages, for shipment to the closest existing industrial centers.

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Other Chemical Processing

The possibilities outlined for recovery of bulk chemicals depend on hydrocarbon processing for which lignite has in general no specific advantage but would be used primarily on the basis of low cost. These processes can be considered to represent the major possibilities for bulk use of lignite for chemical processing. There exist, in addition, a number of further possibilities for chemical use or recovery of chemical products from lignite on smaller scale, in some of which the highly available reactive groups of the low-rank coal substance may be used to specific advantage. Some specialized uses of this type, primarily for lignite from certain highly oxidized deposits, have already been developed, and others may prove feasible. Production of specialized carbons; that is, activated carbon and electrode and electric furnace carbons, may also be required in connection with other industrial processing. In general, applications of this type will not provide large coal markets but can in themselves represent operations with economic value and merit.

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2. EUROPEAN TECHNOLOGY ON LIGNITIC COALS

The primary purpose of this section is to review the developments in European brown-coal technology to provide a gage for the technical possibilities inherent in the large resources of lignite in the North Central States.

In Central Germany, where the economic climate was particularly favorable, a vast chemical empire was built up on the basis of brown coal as the primary raw material, and the technology attained a high state of development just before World War II. Much of the success of the brown-coal industry may be attributed to integration of the numerous phases of the operations into one general pattern.

The importance of integration in the development of the mining, preparation, and utilization of lignite for conversion to power and other higher forms of energy and the production of chemicals cannot be overemphasized. Many fully developed processes may be uneconomical when operated independently, either because of difficulties in obtaining the materials entering into the process or in marketing the products, which often are only intermediates used in subsequent operations, or both. Such processes, however, often become commercially important when they are brought into a well integrated industry.

The greatest example of integration of German industries built on coal is the Leuna plant of I. G. Farbenindustrie A. G. near Merseburg in the Central German brown-coal region. In addition to the 9,000,000 tons of brown coal from nearby open-pit mines used annually at this plant, over 1,000,000 tons of coke and 400,000 tons of brown-coal char (Grude) were used also. The scale of operations in April 1944, just before strategic bombing was begun, is indicated by the following figures: (60). 1/

Water consumption..... gal. per min.	150,000 to 180,000
Steam capacity.....lb. per hr.	4,300,000
Turbine capacity.....kv.-a.	350,000
Outside power connections.....kw.	65,000
Connected load.....do.	390,000
Power consumption (electric).....do.	172,000
Underground cables.....miles	570 (high voltage)
	354 (medium voltage)
Telephone connections.....	About 2,400
Electric motors	18,114
Freight turnover.....tons per year	15,000,000 (incoming)
	1,800,000 (outgoing)
Consumption of brown coal.....	
.....tons per day	25,000 (summer)
	32,000 (winter)
Consumption of Grude coke.....do.	Up to 1,200
Consumption of byproduct coke from	
bituminous coal .....do.	3,300 (summer)
	4,000 (winter)
Consumption of bituminous coal...do.	80 (summer)
	100 (winter)
Consumption of liquid fuels.....	
.....tons per month	50 (during peaks)

1/ Underlined numbers in parentheses refer to citations in the bibliography at the end of this section.

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Number of employees in 1941	33,000	
Low point in 1932	8,700	
Number of employees in Dec. 1944	30,800	hourly employees
	4,100	office workers
	400	technicians, including 210 chemists and 175 engineers

The plant occupied a site 11,600 feet long and 3,500 feet wide. It produced about 80 products, of which the most important were:

1. Synthetic oil.
2. Aviation-fuel blending agents and lubricating oils.
3. Fixed nitrogen.
4. Salts.
5. Methanol and crude isobutyl alcohol (isobutyl oil).
6. Miscellaneous organic chemicals.

In addition, the Leuna plant supplied about 350,000 cubic feet of hydrogen per hour to Bunawerke A. G. Schkopau, the largest German synthetic rubber plant, which had a rated capacity of 6,000 tons per month (38). When this plant was operating at capacity it employed 15,000 persons and required 240,000 kw., of which 130,000 kw. was generated from brown coal incidental to process steam production, and the remainder was obtained from outside sources (53). The operation of the Schkopau plant depended largely on Leuna's hydrogen-producing facilities. Only 2.6 percent of Leuna's hydrogen was earmarked for Schkopau. This, however, was its sole source of supply, and Schkopau's production of synthetic rubber was lost when Leuna's hydrogen facilities were bombed out (59).

The Schkopau plant, in turn, produced 100 barrels per day of synthetic lubricating oil from the excess acetylene, an operation that would not have been economical if conducted independently but was considered profitable when integrated with the Buna-S operations (30).

The Leuna-Shkopau complex of the I. G. Farbenindustrie A. G. at its height produced 13 percent of the German synthetic fuel, 10.9 percent of the aviation fuel, 12.8 percent of the aviation lubricants, 32.6 percent of the synthetic nitrogen, 33.3 percent of the synthetic methanol, 5.2 percent of the high-concentration nitric acid, and 46 percent of the synthetic rubber.

Although the Leuna-Schkopau complex is cited as the greatest example of integration of mining, preparation, and utilization primarily for the production of chemicals, many smaller operations based on brown coal may be cited in which the primary purposes were to generate electricity or to provide domestic fuel. The A. G. Sachsische Werke-Espenhain is an example of a smaller but, nevertheless, very important integrated undertaking.

The center of the Espenhain operations was a power plant having a generating capacity of 220,000 kw., of which 40,000 kw. was consumed in the plant and the remainder fed to the power grid. The daily output of liquid products consisted of some 3,000 barrels of tar and light oil for hydrogenation elsewhere, approximately 1,100 barrels of finished diesel oil having a 45 to 50 cetane number, and about 1,200 barrels of fuel oil.

Integrated with the Espenhain plant was a brown-coal strip mine, which annually supplied approximately 6,000,000 metric tons of raw brown coal, a briquetting plant - stated to be the largest in Germany - producing about 3,000,000 tons of briquets, and a Lurgi low-temperature-carbonization plant in which these briquets were carbonized,

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with a yield of 1,500,000 tons of char, 115,000,000 gallons of phenolic water, 360,000 tons of tar and light oil, and 38,000,000,000 cubic feet of gas. The hydrogen sulfide removed from the gas was converted in a Claus kiln to 24,000 tons of sulfur. The phenolic water and a phenol-containing fraction of the light oil were processed for the recovery of 7,000 tons of crude phenols, which was sent to the adjacent Raschig chemical plant for making synthetic resins. The light oil, amounting to 150,000 tons, was sent to the Brabag hydrogenation plants at Böhlen and Zeitz. The remaining 205,000 tons of tar was processed in the tar distillation, benzol-SO_2 extraction, and ethylene dichloride dewaxing plants, producing 64,000 tons of diesel oil, 71,000 tons of fuel oil, 13,000 tons of hard paraffins, 13,000 tons of soft paraffins, and 12,000 tons of electrode coke. The hard and soft waxes were sold to produce fatty acids, soaps, and lubricating oils.

Of the 1,500,000 tons of char produced annually, 900,000 tons was consumed in the power plant, and the remainder was distributed to various hydrogenation plants for hydrogen production, usually in Winkler generators (6).

Figure 2 presents a composite chart of the integrated operation. This chart is not intended to represent any particular establishment but to outline the possibilities, under favorable economic conditions, for regional development of an industrial complex based on brown coal.

Nature and Distribution of Brown Coals

The designations brown coal and lignite are frequently used interchangeably, and tables giving the analyses of lignitic coals generally include the entire range of brown coals and lignites.

Brown coals and lignites are as widely distributed throughout the world as the coals of higher rank, but their exploitation is relatively unequal because of the varying economic conditions governing their production, processing, and utilization.

The brown coals of Central Germany, which served as the nucleus for the major developments reviewed in this chapter, are principally of the Eocene age. They are generally found close to the surface, contain more than 45 percent moisture, and are unconsolidated and therefore readily won by strip-mining methods for which earth-moving machinery is readily adapted.

The Central German brown coals may be fitted into the A.S.T.M. Classification of Coals by Rank in class IV, lignitic, group 2, brown coal, moist B.t.u. less than 8,300, unconsolidated (1, pp. 652-657).

In chemical composition the range of Central German brown coals is 45.5 to 52.1 percent moisture, 4.7 to 6.8 ash, 23.7 to 30.4 volatile matter, and 16.8 to 21.5 fixed carbon. On a dry, ash-free basis the volatile matter ranges from 56.1 to 63.4 percent and the calorific value from 6,373 to 6,897 calories per gram (11,500 to 12,400 B.t.u. per pound).

Brown-coal lumps of this character, whether large or small, dry from the surface inward. The shrinkage of the outer shell leads to cracking and peeling and ultimately to complete slacking. The moisture content drops to about 15 percent, more or less, depending on the relative humidity of the drying atmosphere.

For an extensive discussion of the nature and distribution of brown coal, reference is made to the contributions by Herman and Edwards (24, pp. 19-85), (25, pp. 1-92).

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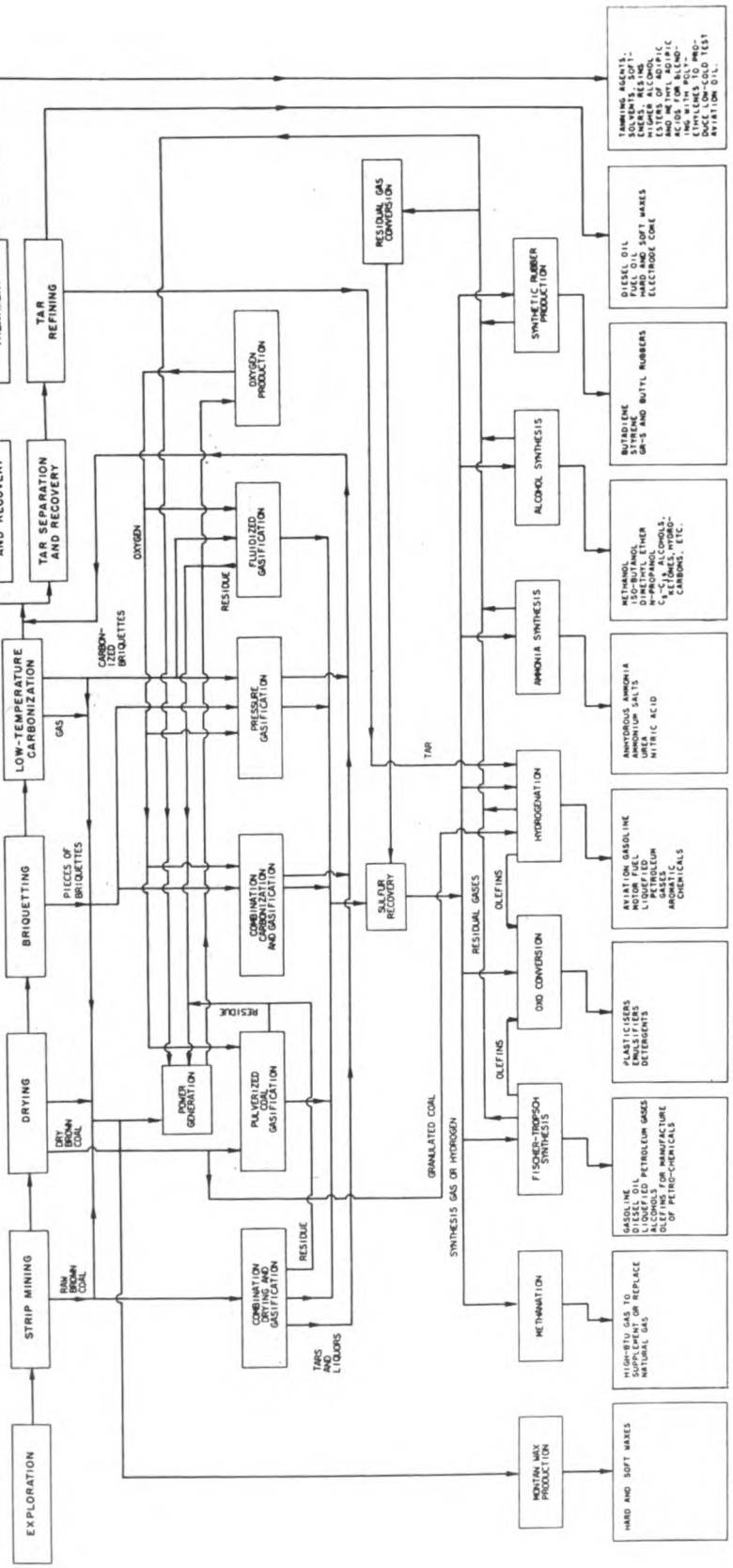

Figure 2. - Integration of German brown-coal operations and some of the products manufactured.

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Strip-Mining of Central German Brown Coal

The average brown-coal field is usually prospected with boreholes. For brown coal and the soft material or strata with which it is usually associated, dry percussion drilling is preferred if a faithful record of all strata passed through is desired. Wet core drilling risks washing away of the soft strata of coal, clays, or sands, with the result that identification of the core layers suffers and the true thickness of the particular beds cannot be ascertained. It is therefore important to employ only dry methods of drilling in developing any deposit and to use wet drilling, which costs about half as much, to clarify the details of the overburden.

Overburden is stripped using multibucket chain or bucketwheel land-dredging machines. The overburden stripping is always carried well ahead of the coal stripping, providing a large area of exposed coal at all times.

The discharge from the dredging machines is preferably loaded on overburden conveyor bridges, which transport the material to the spoil banks. Among the largest of overburden bridges, the one at Böhlen is about 510 meters long and the one at Espenhain 550 meters long.

The coal is generally excavated by the same type of dredging machines as the overburden, although they are not used interchangeably, and any particular machine will probably spend its whole life working on one material without a changeover.

The coal bed is divided into two faces, with the excavating machines operating on the middle bench. The upper face is excavated down at an angle of 75° to the horizontal, and the lower face is excavated up at 45°. The coal is discharged into railway cars on the middle bench and delivered into bunkers of the power plant or the briquetting plant.

For downward excavation a multiclaw variation of the multibucket excavator has been developed. In this development the buckets have been replaced by a series of claws fixed on a traveling chain. These claws pull down the coal and drop it on a heap at the bottom of the face, where it is picked up by a bucket conveyor operating from the same excavator.

Multibucket excavators are capable of working a face 130 feet high and can handle up to 1,000 cubic yards of material per hour. Bucketwheel excavators have an advantage over the multibucket chain type in having double the rated output and in lower power consumption per unit of output. They are also capable of working a face 130 feet high. Multiclaw machines can work on a face 100 feet high and handle 400 tons per hour.

The tracks on the middle bench are moved toward the advancing coal face by special machines. They advance at the rate of 1 foot per pass and are capable of moving 1/2 mile of track over 5 feet in 30 minutes.

Before any mine is opened up, a drainage system is established to bring the overburden into suitable condition for excavation and to remove as much moisture as possible from the coal. This is done by sinking boreholes to the bottom of the coal bed and pumping them by electrically driven deepwell pumps. After the coal face is opened to the bottom of the bed, horizontal holes are drilled, and the water flows through open drainage channels to sumps where pumps, permanently installed, operate throughout the life of the mine.

For a detailed treatise on core drilling, overburden excavation, overburden conveyor bridges, coal excavation, and transport, including a historical outline of developments throughout the world, reference is made to Herman's Brown Coal (25, pp. 93-191). The major considerations for planning the mining of brown coal are reviewed

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by Morgan (24, pp. 86-110). He specifically calls attention to fire hazards when strip mining is conducted in climates with hot, dry, windy conditions prevailing, as in Australia. German experience is described in several reports of the British Intelligence Objectives Subcommittee (11, 15, 44).

These references and their numerous secondary references together indicate that brown-coal deposits must be exploited on a very large scale by highly mechanized strip-mining methods. Unless the scale of operations is large enough to justify the employment of high-capacity machinery, the unit cost of mining the high-moisture-containing brown coal, with its correspondingly low calorific value, cannot be attractive enough to keep the lignitic coal industry in a competitive position with other fuels.

Combustion of Brown Coal or Coke

Brown coal may be burned directly in furnaces specially designed for this purpose. Where the operations are isolated, grinding, drying, and firing of brown coal in one brief stage are less costly and less complicated than drying and then finely pulverizing it.

The Kramer mill coarsely pulverizes, partly dries, and fires the fuel in a matter of a few seconds. The coal falls into a vertical shaft onto a hammer mill, which crushes and throws it upward. Hot air or gases, entering below the mill, mix with and partly dry the coal and are then drawn into the combustion chamber. The velocity of the draft governs the maximum size of coal particle that can be drawn into the furnace. Oversize particles drop back to the mill for further grinding. Ashes and larger unconsumed pieces of coal fall on a grate at the base of the furnace. Secondary air flowing through this grate burns the unconsumed coal. Kramer-mill furnaces are reported to have steam outputs as high as 400,000 pounds per hour.

A variation of the Kramer mill is the KSG (Kohlenscheidungsgesellschaft) mill. In this mill the raw coal, mixed with high-temperature flue gas from the combustion chamber, falls through the shaft to the mill. It is then blown up to a classifier, which allows the finer particles to rise to the combustion chamber and returns the coarser ones to the shaft of the mill. The first large-scale boiler using KSG-mill firing is reported to have an output of 250,000 pounds of steam per hour with coal having a gross calorific value of 4,500 B.t.u. per pound (6, pp. 472-507; 24, pp. 111-149).

Although the Kramer and KSG mill furnaces are mentioned to call attention to the feasibility of direct firing of raw brown coal for steam generation, a discussion of such operations does not properly fall within the scope of this chapter. Direct combustion of raw coal is justified only so long as the products obtainable from carbonization have no greater market value than their fuel value. Such a situation is not expected to prevail in well-integrated operations in which means for utilizing the products of carbonization have been adequately provided.

In Espenhain, for example, where the primary objective was electric power generation, most of the coal was dried, briquetted, and carbonized, and a fraction of the coke was used for generating steam. The coke was supplemented by the gas remaining after all the other process heat requirements have been met. Raw brown coal was used to balance the operations.

The brown coal was pulverized in KSG impact mills and the coke in tube mills and fired tangentially (61, pp. 19-42).

The brown-coal coke was also pulverized at the Böhlen plant of A. G. Sachsische-Werke before firing (61, pp. 5-18).

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Drying Brown Coal

The coal is prepared for drying by crushing and screening to a size suitable for the particular drying system employed.

Baragwanath and Finlayson listed six types of driers used in German brown coal operations (3). These are:

(a) Plate driers - by indirect steam heating.
(b) Rotary tubular driers - by indirect steam heating.
(c) Circulatory gas driers - by flue gas heating (direct).
(d) Mill driers - by gas heating (direct).
(e) Turbodriers - by gas heating (direct).
(f) Fleissner process of direct steam drying.

Herman (25, pp. 192-471, 580) has devoted considerable space to the discussion of drying equipment and has included detailed information on the operating characteristics and requirements of most of the driers falling in the above classification. Bardgett (4), as well as Baragwanath and Finlayson (3), reported on the circulating hot gas drier designed by Buttner Werke A. G. of Uerdingen-Krefeld. This drier is referred to in Buttner catalogs as the REMA-Rosin Schellumlauftrockner and is claimed to be capable of drying 5,000 tons per day of brown coal in the Offleben installation. It consists of 7 units, 6 of which are in service and 1 is a spare (12). The coal is reduced in the driers from a 0- to 25-m.m. size range to 0 to 2.5 m.m. The moisture content is reduced from 48 percent to 13 percent at the rate of 470 tons per day per unit.

Fleissner driers have not been used for drying central German brown coal. Driers of this type are not considered suitable for unconsolidated lignitic coals.

Briquetting Brown Coal

No binders are required for briquetting unconsolidated brown coal; and in this respect brown coal differs to a major degree from the consolidated lignite so abundantly deposited in the North Central States, which are poor in wax and bitumen content and, consequently, require a binder.

Briquetting presses fall into two general classes:

1. Extrusion presses.
2. Ring-roll presses.

Most briquets used for industrial or household purposes are produced in extrusion presses. For carbonization both extrusion and ring-roll presses are used. The briquets from ring-roll presses are dense and slow burning and are generally reserved for subsequent carbonization (3).

In extrusion presses the stamp pressures are usually less than 1,000 atmospheres, but with increasing fineness of coal they rise to as much as 1,600 atmospheres. In the ring-roll press a pressure of 2,000 to 2,500 atmospheres is required. Bardgett has reported on the use of ring-roll presses at Regis (5) and of extrusion presses at Offleben (4). The largest installation of extrusion presses was reported by Bays, Jones, and MacKusick to be at Espenhain (6). Engineering details including power requirements, are fully treated by Herman (25, pp. 192-471) and Baragwanath (3). Spooner has written an historical review of the ring-roll press. He reported accounts of tests on coals normally requiring binders and of forthcoming developments in the ring-roll press (54). He reported that in 1947 there were 7 installations, with a total of 26

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ring-roll presses in operation. At Regis the output per press per 24 hours was 240 tons; and at Nachterstadt (Riebeck-Montan), where the brown coal was particularly suitable for briquetting, the output per press was eventually raised to 500 tons per 24 hours.

Carbonizing Brown Coal

Caseley and others have reported that not all types of brown coal are suitable or can be used economically for low-temperature carbonization. In general, the brown coal of the Lower Rhenish district is unsuitable, whereas that of Central Germany is quite satisfactory (15). Among the plants in Central Germany where large-scale carbonization of brown coal briquets has been in operation the Lurgi-Spulgas process has been employed.

Bardgett has described the operation of the Lurgi-Spülgas retorts in reports covering visits of CIOS and BIOS investigating teams to Regis and Offleben, respectively (4, 5). A Lurgi-Spulgas plant consists essentially of a battery of shafts in which the briquets are carbonized by internal heating. Each shaft is composed of three superimposed sections through which the briquets pass successively. In the upper section the briquets are predried to a moisture content of not more than 0.5 percent before entering the carbonizing section. The bottom section serves as a coke-cooling zone.

The drying and carbonization sections are heated by burning the gases of distillation in adjacent combustion chambers. The distillation gases are preheated in the cooling section.

Before burning, the gases flow through a dust separator, a primary cooler, an electrostatic tar precipitator, a tubular cooler, a booster, and light-oil absorption plant.

The primary products of low-temperature carbonization of brown-coal briquets consist of tar and light oil, coke, phenolic oils, and sulfur compounds recovered from the gas before it is used for heating.

Gas Production

To produce city gas, uncarbonized brown-coal briquets or pieces resulting from the breakage of uncarbonized brown-coal briquets in the course of its handling may be gasified in Lurgi pressure gasifiers with oxygen and steam.

The gas produced has an approximate heating value of 450 B.t.u. per cubic foot and generally meets the European standards for public utility gas distribution. The gas may be passed over a suitable catalyst for converting the carbon monoxide and hydrogen to methane. The resulting gas would then be principally methane and would be interchangeable with natural gas.

Uncarbonized briquets are preferred as the feed to the Lurgi generator. In the course of the gasification, the hot gases distill the incoming charge of fuel and are enriched by the gases of distillation. The tar and light oil and aqueous condensate are recovered in the gas-cleaning apparatus and in integrated operations would be sent to the same tar-refining and phenolic oil plant as the products from the low-temperature carbonization plant.

Very extensive literature is available on the Lurgi pressure-gasification plant. Hollings and others have reported on its operations after visiting the Böhlen installations in 1945 (27, 28). Odell covered the process in a Bureau of Mines publication (47), and Newman in a review of gasification processes using oxygen (46). Brown coal

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or brown coal briquets have been used to produce synthesis gas or hydrogen in generators designed for continuous operation in which the heat required for the reaction is supplied by regenerators instead of oxygen. Schmalfeldt (10, 26, 42), Koppers (4, pp. 2/40-2/41, 33), and Pintsch-Hillebrand (10, pp. 2/30-2/39, 35, 45, 48) processes were devised for this type of operation.

In the Schmalfeldt process the original intention was to feed undried, coarsely crushed, raw brown coal and to depend on the explosive effect of rapid drying in contact with the hot recirculating gases to break the lumps into small particles, which were expected to be entrained by and circulate with the gases. In practice, it was necessary to add grinding equipment. It was also found that the design capacity could not be attained without the addition of oxygen.

Both the Koppers and Pintsch-Hillebrand processes are fixed-bed processes. The incoming briquets flow countercurrent to the hot circulating gases and undergo distillation as in the Lurgi plant referred to earlier in this part. The tar and light-oil content of the briquets is, therefore, virtually fully recoverable.

"Grudekoks", or fines screened from low-temperature coke produced from brown coal, served as the fuel for hydrogen production in Winkler generators operating in several hydrogenation plants in the brown coal regions of Central Germany.

Because of integrated operations, which required tar for hydrogenation, uncarbonized dry brown coal was not used in the Winkler generators. The use of dry brown coal in Winkler generators, with the exception of a higher methane yield, is as satisfactory as that of Grudekoks.

In the Winkler generators a mixture of oxygen and steam is blown through a fluidized fuel bed. As gasification of any given particle of fuel proceeds its size decreases until it becomes small enough to become entrained and be carried out of the generator by the gas stream. As a result, the extent of conversion of the fuel seldom exceeds 60 percent. In an isolated gasification operation this would be a serious loss, but in the German integrated operations this was of little consequence, since with only a small additional amount of handling the unconsumed carbon was used as boiler fuel. The Winkler gasification process, like the Lurgi, has received much attention in the literature (19, 41, 43, 46, 47, 53).

Pulverized brown coal may be gasified in oxygen-blown generators that have undergone considerable development since the end of World War II. The gasification is in entrainment and, with reference to particle size, may be said to begin where the Winkler leaves off. Accordingly, much higher conversion of carbon to gas has been achieved in experimental operations. No commercial gasification of brown coal in entrainment with oxygen and steam has been reported, but the writer's own observation of experimental operations has led him to the conclusion that dried brown coal could be gasified with greater ease and higher carbon conversion than bituminous coal. No references are available to papers describing commercial, pulverized-coal-gasification equipment.

Brown-coal briquets have been gasified commercially in specially designed chamber ovens. The Didier-Bubiag process uses vertical ovens in which the gas offtake is placed two-thirds of the height of the oven below the top, so that the gases and moisture distilled from the fresh incoming charge of briquets must flow past the hot char nearer the offtake. Additional steam is admitted at the bottom. With heat supplied through the refractory wall, the hydrocarbons are partly cracked, and the moisture or steam reacts with the char to produce water gas (10, pp. 2/50-2/55; 57). The briquets are not completely consumed, and the operation is so balanced that there is just enough residual char to supply the gas producers used for generating the gas to heat the chambers.

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Gas Purification and Sulfur Recovery

Gas-purification methods, broadly speaking, are generally similar, whether the gas is produced from brown coal or any of the higher rank coals. The specific purification methods employed are usually described along with the gasification methods employed in the references already cited for the individual gasification processes.

Sulfur is recovered in Claus ovens in which the hydrogen sulfide is oxidized to yield moisture and sulfur. To take care of very large volumes of hydrogen sulfide, the old-type Claus oven was considered inadequate, and new designs were developed.

The essential modification provides for burning part of the hydrogen sulfide separately and cooling the gas in a waste-heat boiler before passing it through the bauxite catalyst. Two tons of steam is thus generated for each ton of sulfur recovered, and the capacity of the bauxite catalyst is increased tenfold (13).

Montan Wax

Brown coal is an excellent source of montan wax. The most desirable brown coal for this purpose, containing 15 percent wax, was found near Halle and processed in the Riebeck'sche plants at Amsdorf and Wansleben. However, coal containing as low as 10 percent wax could be economically processed.

The brown coal is granulated to 5 mm., screened, and steam-dried to a moisture content of 10 to 12 percent. The wax is extracted with a mixture of 85 percent benzol and 15 percent unrefined wood alcohol (containing methyl and isopropyl alcohols) at 90° to 100° C. The alcohols dissolve the cell walls of the brown-coal structure and set the wax free to be dissolved by the benzol. The wax solution is drawn off and the solvent distilled off, leaving the crude montan wax as a residue. The extracted brown coal is freed from solvent by steam and used as fuel. Steinle (55) and Hatt (23), in their respective reports, describe the processes used at Riebeck and Eidelstadt. Other surveys of the wax industry in Germany include discussions of montan wax (2, 16, 49) and methods of refining and utilizing the products.

Montan wax has been used to prepare shoe polish, floor polish, cable wax, rubber compositions for shoe soles and heels, sizing emulsions, and carbon paper; it has also been employed for impregnating textiles, phlegmatizing explosives, preparing lubricating greases, wood hardening, recording waxes, and numerous other applications.

Tar Refining

Rhodes (51) has reported that about 91 percent of the low-temperature tar produced in Germany in 1943 came from brown coal. This included 84 percent that came from Lurgi-Spülgas retorts and 7 percent from Geissen, Borsig-Geissen, and Rolle retorts. Of the brown-coal tar, 25 percent was distilled to produce diesel and heating oils, hard and soft paraffin wax, and electrode coke. The remaining 75 percent was hydrogenated to motor and fuel oils.

Methods of treating the brown-coal tar are fully reported by Rhodes (51), also by Jones (36), and others (6, 31).

Phenol Separation and Recovery; Phenolic Oil Plants

A process of dephenolization by solvent washing was developed by I-G for waste waters from hydrogenation and low-temperature carbonization. The solvent used was tricresylphosphate, which was regenerated by vacuum distillation. However, the removal of

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high-boiling phenols was found to be quite difficult, and their accumulation thickened the tricresylphosphate, with subsequent emulsification troubles.

An important process, applicable for cleaning up hydrogenation waste liquors and low-temperature carbonization waters, such as from the Lurgi-Spülgas process, utilizes a special solvent called phenosalvan. This is essentially isobutyl acetate. No emulsification difficulties are encountered in its use, and the solvent losses are low.

The largest plant for processing tar acids recovered from hydrogenation and low-temperature carbonization was at Leuna. The tar acids, whether extracted by tricresyl-phosphosphate, phenosalvan, or other processes, were brought into the Leuna south phenol plant, where, after some preliminary treatment, they were combined and processed together.

Rhodes (51) briefly covered 10 processes and products and provided numerous references to plant and equipment layouts and descriptive literature as follows:

1. Tar-acid extraction and processing at the Leuna coal-hydrogenation plant.
2. Pretreatment of the separately derived crude-tar acids.
3. Fractional distillation of refined tar acids.
4. Sulfuric acid refining of crude cresol.
5. Production of pyrocathecol.
6. Hydrogenation of phenol to cyclohexanol.
7. Production of cyclohexanone.
8. Manufacture of cyclohexanone oxime and caprolactam.
9. Manufacture of adipic acid.
10. Manufacture of polymeric amides.

Flowsheets of the individual processes are included in the report.

Hydrogenation Plant

The first commercial hydrogenation plant to produce synthetic gasoline was built in 1927 in the I. G. Farben plant at Leuna. It was natural to choose Leuna because the hydrogen-production capacity of the nitrogen plant was more than was required for the manufacture of synthetic ammonia and the staff had wide experience in the field of catalytic reactions under high pressure.

By the end of World War II the number of hydrogenation plants grew to 12, with an aggregate oil-producing capacity of about 4,000,000 metric tons (25, pp. 573-581). Actual production during the first quarter of 1944 was at the rate of 3,780,000 metric tons per year of petroleum products (59). Brown coal and brown-coal tars, from the carbonization of briquets, were the principal raw materials. The main products were motor fuels, diesel oil, fuel oil, paraffin wax, and lubricating oils. At least 85 percent of the German aviation fuel was produced by hydrogenation.

The process consists in pumping a mixture of about equal parts of recycle heavy oil and powdered coal along with hydrogen at about 200 atmospheres pressure

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into reactors whose temperature is maintained at about 475° C. A small amount (0.1 to 1 percent by weight of the coal) of powdered catalyst is included in the coal-oil paste. During 1 to 3 hours at 475° C., the coal is converted to a heavy oil, which is recycled to be mixed with powdered coal. The heavy oil is converted to "middle oil", the bulk of which boils in the range of 200° to 350° C. at atmospheric pressure. This middle oil is sent to the second stage of the process, where it is vaporized in a stream of high-pressure hydrogen and passed through fixed beds of catalyst granules or pellets. The middle oil is thereby converted to gasoline (62).

Details of the hydrogenation operations at Leuna on Central German brown coals and tars are reported by Holroyd and Faragher (30) and those at Troglitz-Zeitz (20) and Bohlen (19) by Ellis. Details of the hydrogenation methods employed for Rhenish brown coal are given in reports on the Wesseling plant (45, 48).

Fischer-Tropsch Plants

The synthesis of hydrocarbons from carbon monoxide and hydrogen is generally called the Fischer-Tropsch process, named after Franz Fischer and Hans Tropsch, who began its development in 1923.

The Fischer-Tropsch process was of secondary importance in the German fuel economy, producing less than 10 percent of the total German oil supply. The greatest obstacle to large-scale development of the process was the poor quality of the gasoline it produced. With the beginning of the war only a short time away, the Germans had to use other means to synthesize high-quality fuels, such as high-pressure hydrogenation, and in the same measure as hydrogenation capacity was increased, the expansion of the Fischer-Tropsch process was brought to a standstill.

In the brown coal region of Central Germany two Fischer-Tropsch plants were operating: Braunkohle Benzin A. G. at Schwarzheide-Ruhland, the largest Fischer-Tropsch plant in Germany, with an annual capacity of 170,000 tons of product, and the Wintershall A. G. plant at Lutzkendorff, with an annual capacity of 12,000 tons of product (50).

The synthesis gas at Schwarzheide-Ruhland was produced from brown-coal briquets in Didier-Bubiag vertical retorts (10, pp. 2/50-2/55; 57) and in Koppers recirculating gas generators (4, 22, 33). At Lutzkendorff brown coal was gasified in Schmalfeldt generators (42).

The products of Fischer-Tropsch plants using cobalt catalysts generally consisted of C_3-C_4 hydrocarbons, low-octane gasoline, diesel oil, and waxes. Byproducts of the Fischer-Tropsch process have numerous uses in the production of other chemicals.

A vast literature on the Fischer-Tropsch process is available. The basic chemistry of the process, the results of catalyst testing and pilot-plant development work, and data on industrial operations have been presented in a Bureau of Mines review (56). Considerable attention is given in this review to developing iron catalysts and to improving the quality of the gasoline that results from their use. Tramm (58), in a more recent contribution, discussed the postwar economics of the process as they apply to European conditions. He concludes that a combination of the Fischer-Tropsch process with pipeline-gas projects offers fine possibilities. It is his opinion that integration of pressure gasification with Fischer-Tropsch synthesis will prove most economical.

Methanation of Gas

Gas containing carbon monoxide and hydrogen may be improved in heating value by catalytic synthesis of methane from these gases.

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At Leipzig a Fischer-Tropsch unit was under construction at the gasworks. The purpose of the plant was to produce a high calorific value gas with liquid byproducts. The plant was 75 percent completed when the Eastern Zone of Germany was placed under Russian control (32).

Ruhrchemie developed a process for methane synthesis having as its primary objective the supply of methane-enriched coal or coke oven gas as road transport fuel. The carbon monoxide and hydrogen in the gas was synthesized to methane over a nickel catalyst, using magnesia as a promoter (34).

The catalytic synthesis of methane for gas manufacture has been under investigation in England, and a nickel catalyst was developed for this purpose (18). The Bureau of Mines used this catalyst for enriching the gas produced in a pilot plant for pressure gasification of solid fuel in a fixed-bed generator. The gas on a CO_2-free basis was mostly methane, had a calorific value of 900 B.t.u. per cubic foot (17), and could be used as an excellent supplement to or substitute for natural gas.

Oxo Process

Olefins may be obtained from Fischer-Tropsch, hydrogenation, and several other operations in a system designed for full utilization of brown coal. The oxo process may therefore be readily integrated with the system.

> The word "oxo" is derived from the German term "Oxierung," meaning ketonization. The oxo reaction is the catalytic addition of carbon monoxide and hydrogen to an olefin to form aldehydes containing one more carbon atom than the olefin used. The aldehydes usually are reduced with hydrogen to primary alcohols in a second stage. This two-stage procedure is known as the oxo process... (20, p. 441).

The products resulting from the oxo reaction depend on the boiling range of the feed olefin. If ethylene is used, the product is propionaldehyde; propylene yields butanol; butylene yields amyl alcohol; C_5-C_{12} olefins yield mainly branched-chain alcohols useful as plasticizers; and highly branched olefins, such as polymers of propylene and butylene, yield more highly branched alcohols, the sulfates of which have good wetting properties; C_{12}-C_{18} olefins also yield alcohol for the manufacture of alcohol sulfates and were considered most important for the manufacture of detergents; and C_{20} and above yield wax alcohols that are outstanding emulsifiers (29). As a source of olefins, the Fischer-Tropsch-process oils and waxes are considered excellent. The waxes must be cracked, but the olefins from the cracked waxes have been reported to give better detergent products.

The oxo process, integrated into a large-scale brown-coal development, would provide an outlet for olefins from many other operations in addition to that of the Fischer-Tropsch and wax manufacture.

Ammonia Synthesis

The synthesis of ammonia requires a supply of synthesis gas composed of 3 parts hydrogen and 1 part nitrogen. The hydrogen may be obtained by gasification of brown coal. Nitrogen may be obtained as a byproduct of the production of oxygen, which is most likely to be used in the modern practice of gas production from low-rank coal.

Gasification methods have already been referred to and references supplied. The synthesis of the ammonia itself is one of the oldest of the industrial chemical syntheses and is well known, and the details of the various processes have been widely published in the literature. Accordingly, no attempt will be made here to furnish references to the various techniques employed in the synthesis operations.

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The products from ammonia have been equally well treated in the literature.

Synthetic Methanol

The synthesis of methanol requires gas composed of 2 parts hydrogen and 1 part CO. This gas is produced essentially for the Fischer-Tropsch or ammonia synthesis, and integration of the three processes provides considerable flexibility of operation. Ammonia, methanol (and higher alcohol) syntheses as practiced at Leuna are briefly described by Morley (30, chaps. 2 and 3).

Oxygenated compounds are also made simultaneously with oil fractions in Fischer-Tropsch operations (56).

Synthetic Rubber

The manufacture of synthetic rubber in the Central German brown-coal region was integrated with the ammonia, alcohol, liquid-fuel, and other synthesis operations in the Leuna-Schkopau complex.

Schkopau was the largest synthetic rubber plant in Germany. It was capable of producing 6,000 tons of Buna S-3 per month when the supply of hydrogen from Leuna was not interrupted.

The base of most of the Schkopau products is calcium carbide. This is produced by conventional methods from lime and coke in carbide furnaces. Power requirements are 3,300 kw.-hr. per ton of carbide and 18,000 to 19,000 kw.-hr. per ton of Buna-S. The carbide is converted to acetylene, using a water-slackening process, which produces virtually dry calcium hydrate. Half of the hydrate is reused to produce burned lime, and the other half is sold for agricultural purposes.

Butadiene is produced from aldol by converting acetylene to acetaldehyde, most of which is converted to aldol and the balance to acetic acid. The aldol is reduced with the hydrogen to butol (2,4-butanediol), which in turn is dehydrated to butadiene.

Styrene is produced from benzene and ethylene obtained by the conversion of acetylene to ethylene by hydrogenation. (Ethylene is also produced by passing alcohol vapor over activated alumina.) The ethylene is combined with benzene to form ethylbenzene, which in turn is dehydrogenated in the presence of steam over a catalyst to produce styrene.

Buna S-3 is produced by emulsion polymerization in a continuous process from butadiene and styrene, with an emulsifier manufactured from butanol, naphthalene, sulfuric acid, and oleum (21, 38). Livingston (39), Boundy and Hasche (7, 8, 9), Wood (63), and Krieble (37) have reported on the methods of manufacturing several intermediate products and end products. Calcott (14) listed 23 products and the processes used for their manufacture at Schkopau in his report to the Chemical Warfare Service.

Miscellaneous Chemicals

It is not practical in this section to list the miscellaneous chemicals that have been produced from or incidental to brown-coal operations. It may be said with certainty that brown coal may serve as a source of the same type and variety of chemicals as natural gas or oil, on which huge chemical empires have been built.

Brown coal may be the source of most of the essential intermediates that go into the production of the newer fibers, like nylon, dynel, acrilan, dacron, orlon, and many other products based on chemical polymers, rather than regenerated cellulose type.

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> Any manufacture of synthetic fibers must be integrated from a raw materials point of view, not only from an availability standpoint but particularly from the continuing importance of lowering cost of fibers and the necessity of having control of raw materials to do this (52).

Brown coal yields the necessary hydrocarbons, principally obtained from petroleum and natural gas in the United States, which serve as a base for the American petrochemical industry. The capital investiment in the industry in 1951 is estimated at almost 2 billion dollars, and up to May 1, 1952, DPA has issued Certificates of Necessity for another $717,000,000 or 36 percent of the total (40). The production of petrochemicals, like the newer synthetic fibers, has been thriving most where it is integrated with the operations of the larger chemical companies. This is indicated by the chemical manufacturers accounting for 80 to 85 percent of the total volume of production and the petroleum companies only 15 to 20 percent.

Conclusions

In this chapter an effort was made to review the developments in brown-coal technology and treat them as an integrated operation. No attempt has been made to cover all phases of the subject. The technical possibilities are literally unlimited, and the scale of the operations may be made as large as the economic situation will permit.

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3. OCCURRENCE AND PROPERTIES

The word "lignite" has had quite varied usage. Some writers have used this word exclusively for carbonized fossil wood, rather than for a rank of coal. German coal petrographers sometimes have used Lignit for the fossil wood that makes up a part of the Tertiary coal (Braunkohle) of Germany. In this country the term "lignite" was formerly used as a loosely defined generic name for low-rank coal. Thus, what is now known as subbituminous coal in many of the Western States was formerly often called "black lignite". On the other hand, local occurrences in this country of what German coal petrographers would almost certainly call Braunkohle have been named lignite. The small deposit of Tertiary coal near Brandon, Vt.(3),1/ is a good example of this generic use of the word lignite. The German coal scientists have used Braunkohle in a similar generic sense. For example, they frequently refer to the lignite deposits of our Northern Great Plains region as Braunkohle. In other countries, one or the other of these practices has been followed. The Japanese and the Indians refer to their deposits of lowest rank coal as lignite. The Australians, on the other hand, call their considerable deposits "brown coal".

The ASTM classification (1, 36) established 8,300 B.t.u. per pound on the moist, mineral-matter-free basis as the upper limit for lignite and brown coal. The ASTM classification makes no distinction between lignite and brown coal other than that lignite is said to be consolidated and brown coal unconsolidated. This classification deals with brown coal and lignite as a unit, called Class IV. lignitic.

In the future, valid criteria will probably be found by which the class lignitic coal can be subdivided. At present, however, it should be recognized that brown coal and lignite are generic terms, each applied by some scientists to all lowest rank coal. The best practice for the present is to use the well-defined expression lignitic coal.

Geologic Features of Lignite

The organic origin of coal from peat is an undoubted fact. It now seems almost certain that a constant feature of the history of the earth, since the origin of vegetable matter, has been the formation of peat; that is, accumulations of plant parts and products in various stages of degradation by chemical and biochemical processes. Some periods of earth history have seen widespread formation of peat over a very long period - for instance the Pennsylvanian period of the Paleozoic era. Part of the Pennsylvanian is contemporaneous with that time interval appropriately called the coal measures in Great Britain. At other times, relatively little peat was formed, as, for instance, during the bulk of the Triassic period. Of course, the only way we have of knowing about this peat formation is that subsequent chemical changes have converted it to various kinds of coal.

The existence of a large deposit of coal is due to a combination of circumstances - a large original deposit of peat, then preservation of the peat by formation of covering sediments and by conditions preventing erosion. Therefore, a period that seems to be characterized by absence of coal may appear that way only because no part of the geologic record of that period has preserved peat deposits that were being formed. The time in which we live has the geologic features of a coal-barren period, for example, high land masses and prominent deserts. Yet there are many places on earth where peat, which could become coal, is being formed.

1/ Underlined numbers in parentheses refer to citations in the bibliography at the end of this section.

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Alteration of the original plant material to peat and then coal is a complex process. There are, of course, biological changes that take place in the plant material during the formation of peat. These changes may be rather pronounced if the material is amenable to decay and the conditions in the place of deposition favor decay organisms. If the conditions in the water in which the plant material is deposited do not favor decay or the plant parts are decay resistant (as certain waxy fractions are, for instance), biological decomposition may affect the plant material relatively little.

After the peat has been covered by sand, clay, or other sediments, the coalification changes that occur are not affected by biological processes. The first stage in conversion of peat to coal is simply compaction by gravity. This stage is sometimes called diagenesis (33). Subsequent alterations by which the material is converted to coals of various rank are then called metamorphosis. In the course of alteration to a typical lignite, the original peat loses water, which forms about 80 to 90 percent of raw peat, and volatile matter, which makes up about 50 to 60 percent of the dry matter of peat. The percentage of carbon, about 40 to 50 percent of the dry matter of peat, increases. A typical raw North Central States lignite, for comparison, is about 35 to 40 percent moisture. The dry lignite is about 45 percent volatile matter in the proximate analysis and about 70 percent carbon on ultimate analysis. The thermal value of dry peat is somewhat inconstant but usually is in the range of 7,000 to 9,000 B.t.u. per pound (12). Dry North Dakota lignite has a thermal value of about 12,000 B.t.u. per pound.

Alteration of lignitic coal to coal of higher rank takes place by further operation of the processes that made lignite from peat; that is, decrease of moisture and volatile matter, and increase of the percentage of carbon. The thermal value increases as moisture and volatile matter decrease - to a maximum of about 15,000 B.t.u. per pound for low-volatile bituminous coal on the moist, mineral-matter-free basis (the upper limit for lignitic coal being 8,300 B.t.u.). As the percentage of carbon increases to semianthracite, anthracite, and meta-anthracite, the heating value decreases somewhat, to less than 14,000 B.t.u. per pound.

The geologic conditions that control increase in rank vary widely. The metamorphic process will procede slowly, even in the absence of great geologic stresses; that is, peat that was shallowly buried and never subjected to great pressure or other metamorphic agents of great magnitude will become lignitic coal in time. Many shallow occurrences of lignitic coal probably have never been deeply buried; but without operation of metamorphic agents, the geochemical processes that result in elevation of rank beyond the lignitic stage occur very slowly or not at all. Numerous occurrences of coals of lignitic rank far exceed in age other coals of higher rank. Another illustration of the importance of metamorphic agents is that in one region beds of the same age may be of varying ranks, depending on the metamorphic forces that have applied in different parts of the region. For example, the commercially important lignite of North Dakota is part of the Tongue River member of the Fort Union formation (Paleocene). In Wyoming and Montana, coal of this same member, apparently with an identical history of deposition, is predominantly subbituminous in rank. Furthermore, nearly all of the western coal outside of the Fort Union region is of subbituminous or bituminous rank, yet is of Eocene age, that is, somewhat younger than the Fort Union lignite. Here the crustal movements to the west seem the obvious explanation. In fact, the geologic evidence supports the idea that most increase in rank of coal is a function of diastrophic force and/or the gravitational force of the overlying sediments. Geologic pressure has been the prevailing method of metamorphism; but geologic pressure, whether caused by depth of burial or by diastrophic movement, is inevitably accompanied by some temperature elevation, and this has also been a factor in increase in rank. However, many investigators have pointed out the unlikelihood that temperatures above 100° to 300° C. have been important in coal genesis. Kirchheimer (28), for instance, showed

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by experiments on spores that the state of chemical and structural preservation of spores in bituminous coal makes it exceedingly unlikely that high temperatures could have been operative during the coalification process. (Intrusion of hot material near a coal bed can carbonize it locally, but relatively few coals have been thermally metamorphosed in this way.)

Lignitic coal, then, is simply a stage in the continuous sequence of coal ranks. It is only arbitrarily separated, for reasons of convenience, from peat, the basic carbonaceous material from which all coals have been derived, and from subbituminous coal, which represents the arbitrary next higher step in the progressive dehydration and devolatilization that must take place for increase in rank but which by no means takes place at the same rate for all coals. There is also a purely abritrary division between coals and certain related carbonaceous rocks. The threshold percentage of clayey mineral matter that a coal must have to cease being a coal and become a shale is commercially determined. If marketable as fuel in a given situation, the rock is coal, otherwise carbonaceous shale or bone.

Geologic information on the occurrence of lignitic coal is not to be expected in the sense that it is available for petroleum, the occurrence of which requires very special geologic conditions. Formation of the original peat deposit requires the rather special conditions of swamps, or shallow ponds, lakes, or estuaries that were littered with vegetable matter in great quantity while the water level maintained itself despite this sedimentation; but, once the mass of peat was formed, the necessary geologic conditions for lignite to occur are not unusual. The beds must be protected by a cover of sand, clay, or other sediment. This can be very shallow - only a few feet in some instances - or the cover may be thousands of feet or more thick. (Some North Dakota lignite has been measured at depths of over 1,000 feet, yet there is no evidence that this difference in depth of overburden has made any appreciable difference in the nature of the lignite in the millions of years that have followed deposition of the sediments.) To remain lignitic in character, the deposit must also have been relatively little affected by geologic stress; that is, diastrophic forces. As shown above, coal from the same member of the same formation as North Dakota lignite (perhaps some of the same beds, though this has not been established) has become subbituminous in diastrophically more active Montana and Wyoming.

Geologic Features of Fort Union Lignite

The lignite of the Fort Union region is a dense, irregularly banded medium to very dark brown substance. It usually is compact and feels moist when freshly mined. The lignite cleaves easily parallel with the bedding but has little natural tendency to vertical cleavage. As a result, in mining it commonly breaks out in very large slabs, which may be a yard or more across. Although the deposits are predominantly compact, lenses of soft, fibrous mineral charcoal (fusain) that are jet black frequently are seen, and soft, earthy lignite is also found. This earthy variety sometimes predominates in part of a bed. Most of the compact lignite is woody, and this always is apparent in preparations studied microscopically and is often obvious to the naked eye. Frequently parts of logs are encountered in which the wood retains some woody resilience when freshly mined. All Fort Union lignite degrades rapidly in size when exposed to the atmosphere. The coal loses part of its water content, shrinks, and cracks. This is called weathering or slacking. Alternate wetting and drying expedite the process.

A map of the deposits of lignitic and subbituminous coal in the United States (37) is presented in figure 3, showing the extent of Fort Union lignite and other deposits. The entire dotted portion of the Northern Great Plains province represents the Fort Union lignite region. The region also extends into Saskatchewan and a very

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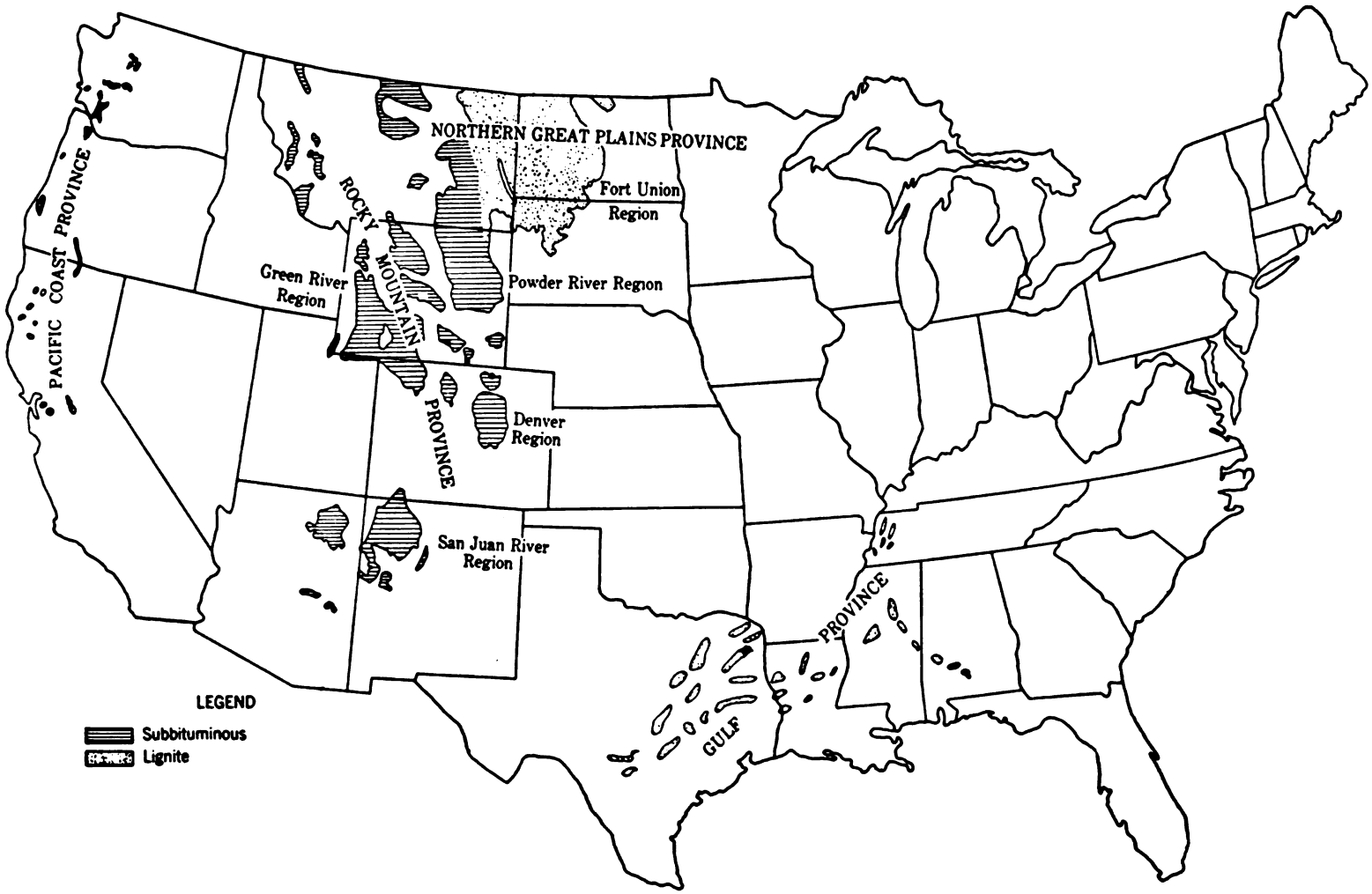

Figure 3. - Lignite and subbituminous-coal deposits of the United States.

All of the dotted portions of Montana, North Dakota, South Dakota, and Wyoming are the Fort Union lignite region, which also extends northward into Canada.

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small area of Manitoba, although this is not shown on the map. Figure 4 is a photograph of a North Dakota lignite bed outcropping in a road cut, demonstrating the frequently very shallow occurrence of the bed. A bed exposed by power shovels in a strip mine is shown in figure 5. The massiveness of an exposed lignite bed in one of the larger mines is illustrated in figure 6.

All lignite mined in North Dakota is in the Fort Union formation of Paleocene age. This formation, which extends into Montana, South Dakota, Wyoming, Saskatchewan, and Manitoba, is the dominant geologic feature in North Dakota south and west of the Missouri River. In the western half of North Dakota, north of the Missouri, the Fort Union formation is covered by Pleistocene glacial drift but is abundantly exposed. It is the principal formation of that region. The North Dakota Badlands in the southwestern part of the State are carved principally from the Fort Union. The Turtle Mountains, of Bottineau and Rolette Counties (and adjacent Manitoba), are an outlying portion. In the region dominated by the Fort Union, the underlying Cretaceous sediments (Pierre shale, Fox Hills sandstone, and especially the Hell Creek formation) outcrop in a number of places, and the overlying Eocene (Golden Valley formation) and Oligocene (White River formation) sediments occur as remnants above the Fort Union. The Fort Union formation in North Dakota is composed of clays (often called shales), sandstones (often very little consolidated), and lignite. Brant (4) notes that nearly all the important beds of lignite are in the Tongue River member of the Fort Union formation, with lesser amounts in the underlying Ludlow member and the overlying Sentinel Butte shale member. As noted by Roe (32), the prevailing colors of the Fort Union formation are gray and yellow. The Tongue River member is lighter in color than the underlying Ludlow and the overlying Sentinel Butte shale member. The lignite beds themselves, which Roe (32) has estimated to be about 100 in number and to contribute 10 percent of the total thickness of the formation, are a striking feature of large exposures, as in badland topography or river cuts. An enormous amount of North Dakota lignite has burned in the ground from fires starting at such outcrops, baking the overlying clays to a natural brick or clinker (often incorrectly called scoria). This material is orange to pink or red and is strikingly characteristic of many parts of the Fort Union region. In some parts of the region, coal is now burning in place, for example, near Amidon, in Slope County, N. Dak.

As Brant (4) and Roe (32) have indicated, there is little structural variation in the North Dakota portion of the Fort Union region, aside from the Glendive anticline - from which the Fort Union has been eroded, exposing Cretaceous rock - and several other relatively small structural features. The lignite beds and the rest of the formation are almost flat lying. Roe (32) estimates the average dip at 20 feet per mile. In large exposures, as along the Missouri River, the apparent planeness of the beds is very striking. Relative freedom from structural complication, such as folding and faulting, will much simplify stratigraphic work with the lignite beds in this region; that is, establishing the vertical sequence of the beds will be relatively easy. It will eventually become important to be able to identify and correlate the lignite beds. This has been true in all the principal coal regions of the world. When this becomes necessary, correlation should be relatively simple in the Fort Union region because of the undisturbed sequences of beds. Petrographic features, as well as the content of plant microfossils (especially pollen and spores), generally make possible identification of a questionable coal bed, providing that the sequence of beds has been established from studies in other localities in the same region. In regions where there is much faulting or other displacement of beds, establishment of the original correlations is difficult and identification of an unknown bed correspondingly hampered. In the Fort Union region, geologic evidence as to dip of beds and exact elevation will usually suffice to identify part of a doubtful bed with other nearby occurrences of the same bed. However, long-range correlation and identification, even in the Fort Union region, will demand petrographic and paleobotanic studies to establish the stratigraphic sequences and identify questionable beds.

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Figure 4. - Outcrop of lignite.

This outcrop (Coteau bed?) occurred in a road cut of North Dakota highway 15, near Quality lignite mine, Ward County, N. Dak.

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Figure 5. - Coteau lignite bed in Miller mine, Ward County, N. Dak.

The lignite bed was approximately 12 feet thick with about 50 feet of overburden (Fort Union clay and glacial drift).

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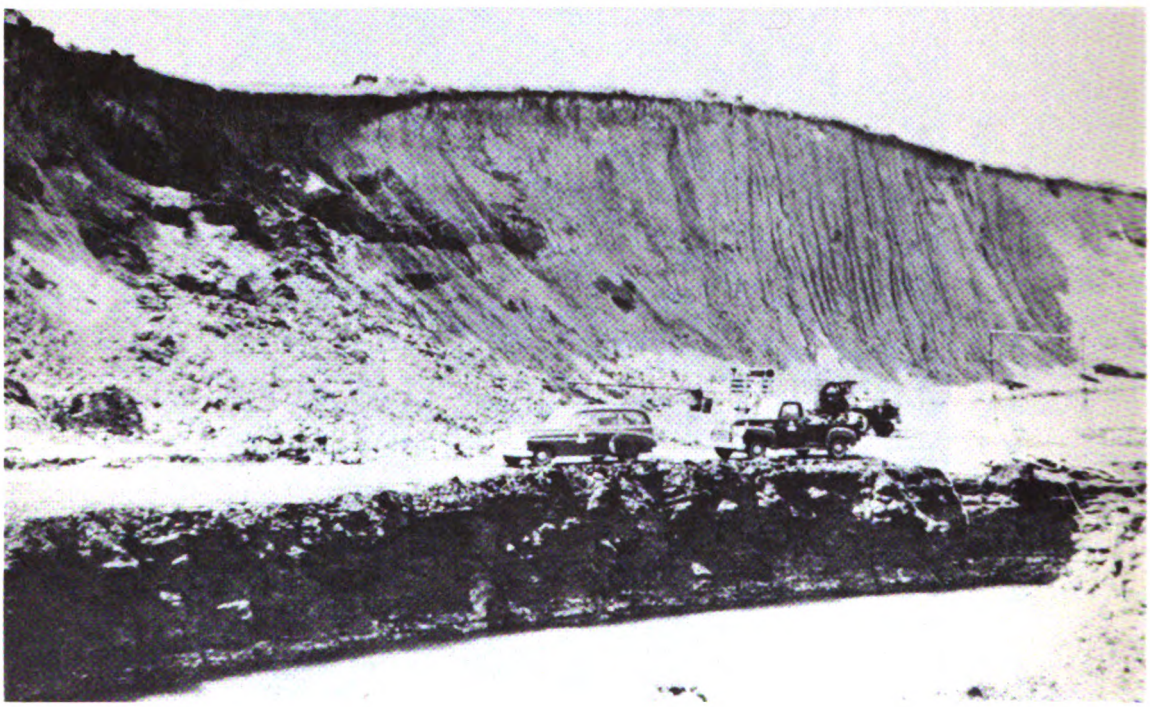

Figure 6. - Coteau lignite bed in Truax-Traer Velva mine, Ward County, N. Dak.

The vehicles shown are parked on a road made on a surface of the massive coal bed, 18 feet thick. The overburden which has been stripped off the coal, was about 40 feet thick. The cut surface of overburden can be seen in the background. The upper part of the overburden is glacial sand and gravel, the lower part Fort Union clay.

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Areal Extent of Lignite Beds in North Dakota

Several estimates of the areal extent of the lignite-bearing Fort Union in North Dakota place this area at about 30,000 square miles. Brant (4) estimates that 28,000 square miles is underlain by beds more than 2.5 feet thick and 4,000 square miles by thinner beds. Beds 10 feet thick or more are common in the region. Beds 15 to 20 feet thick are mined in several places, as in the Coteau bed, Ward County. The Harmon bed, Bowman County, as mined at the Peerless mine, Gascoyne, is 30 feet thick.

Erratic Occurrences of Lignite

Pebbles of lignite have been found as glacial erratics in many places in North Dakota outside the Fort Union region. This has occasionally given rise to rumors of the discovery of new lignite deposits. In one instance, such pebbles were collected from glacial drift near Hamar, Eddy County, in 1952.2/ The pebbles ranged from 1 to 4 inches in diameter and were rounded smooth by erosion, apparently by stream action. The lignite is apparently Fort Union coal, and the nearest plausible source of origin is the Turtle Mountains of Rolette and Bottineau Counties, about 100 miles from Hamar.

Reserves of Lignitic Coal

Because utilization of coal in many parts of the world has been largely restricted to bituminous coal and anthracite, the fact that lignitic coals make up a large fraction of the total world coal reserves has frequently been given only limited attention. Geologists often give the lignitic coals only brief mention in general texts, while the story of coal is told in terms of bituminous coal and more specifically of the bituminous coal of Carboniferous age, which has provided the basic fuel for modern industrial development.

However, data of the World Power Conference (6, 7), as modified by Averitt, Berryhill, and Taylor (2), show that the probable total reserves of world coal are approximately 5,009 x 10^9 metric tons, of which 853.9 x 10^9 metric tons, or 17.0 percent, is brown coal and lignite. These are incomplete figures because of the unavailability of accurate modern data for much of the world.

In the United States, the figures published by Averitt, Berryhill, and Taylor (2), show the total remaining coal reserves of this country to be 1,899 x 10^9 short tons, or approximately 1,723 x 10^9 metric tons. Remaining coal reserves are the estimated reserves that were in the ground before mining less twice the tonnage mined. This deduction is made because the estimated mining losses are thought to have been equivalent to the tonnage mined; that is, average recovery has been about 50 percent. Of the total remaining tonnage of coal reserves in the United States, 463 x 10^9 short tons, or approximately 420 x 10^9 metric tons, is lignite. This constitutes 24.4 percent of the reserve coal tonnage of the United States. This percentage of United States coal reserves in the form of lignitic coal is of the same order as the comparable percentage for the whole world. On the basis of heat-energy content, Averitt, Berryhill, and Taylor's figures for coal reserves show that 15.2 percent of the heat energy available in United States coal reserves is in the form of lignite. World and United States reserves of lignitic coal are presented diagrammatically in figure 7.

The new figures published by Averitt, Berryhill, and Taylor are based on reestimations of the reserves of several States, including Brant's (4) for North Dakota. Brant's reestimation of North Dakota reserves from the former figure of 600 billion short tons to 350 billion short tons. This change was largely responsible for reducing

2/ Collected by Bureau of Mines, Grand Forks, N. Dak.

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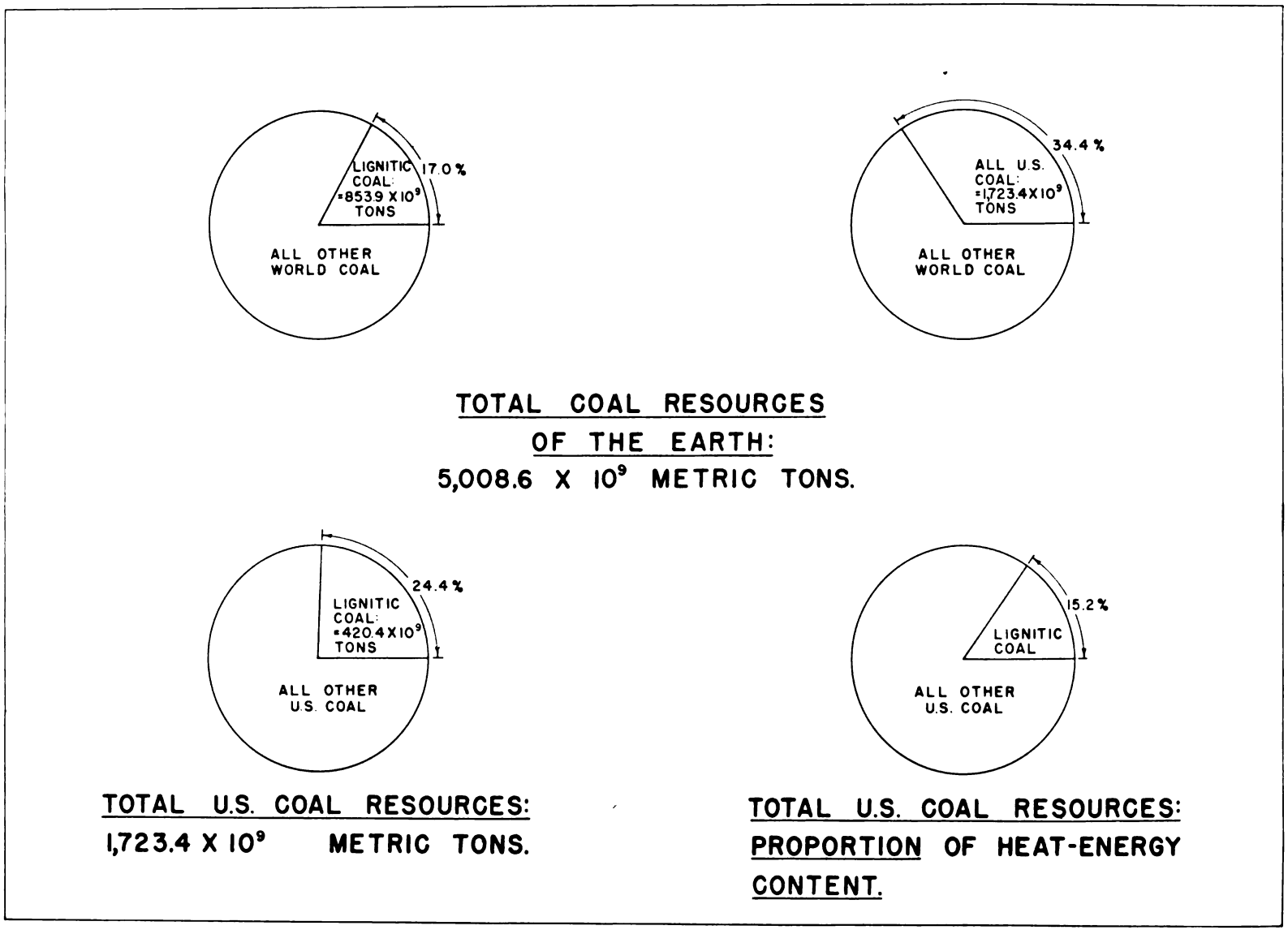
LIGNITIC COAL: =853.9 X 10⁹ TONS
17.0 %
ALL OTHER WORLD COAL
ALL U.S. COAL: =1,723.4X10⁹ TONS
34.4 %
ALL OTHER WORLD COAL
TOTAL COAL RESOURCES OF THE EARTH: 5,008.6 X 10⁹ METRIC TONS.
LIGNITIC COAL: =420.4X10⁹ TONS
24.4 %
ALL OTHER U.S. COAL
LIGNITIC COAL
15.2 %
ALL OTHER U.S. COAL
TOTAL U.S. COAL RESOURCES: 1,723.4 X 10⁹ METRIC TONS.
TOTAL U.S. COAL RESOURCES: PROPORTION OF HEAT-ENERGY CONTENT.

Figure 7. - Distribution of world and United States coal resources between lignitic and higher rank coals.

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the percentage of lignite in the total national reserves from 29.3 percent to 24.4 percent on a tonnage basis and from 18.8 percent to 15.2 percent on a heat-energy basis. North Dakota remains the first State in tonnage of estimated coal reserves, with Montana second. On a heat-energy basis, North Dakota reserves, as reestimated, are also first, by a smaller margin. Based on reserves of lignite in North Dakota, as reestimated, 75.7 percent of the total United States lignite reserves are in that State. The Fort Union region as a whole provides 95 percent of the lignite reserves of this country; hence, figures given above for lignite reserves of the United States are essentially the same as figures for the Fort Union region alone. Future estimates of lignite reserves should include better data for significant deposits of lignite in Tennessee, Mississippi, Louisiana, and Alabama. The data of Averitt, Berryhill, and Taylor (2) include an estimate of reserves in Texas and Arkansas. Louisiana is lumped with California in Other States at what is probably a low figure.

Although these estimates of reserves are probably of the right order of magnitude, some reservations should be made. Estimates for most of the States have been made separately and at different times. In addition, many estimates are more conservative or made to more exacting standards than others. As a result, the figures are not strictly comparable but represent the best data now available.

Culbertson, who has studied part of the Fort Union region, believes that more detailed studies of the region are more likely to increase the proved reserves than to decrease them.3/ He notes that drilling frequently reveals beds to be considerably thicker than they were estimated to be from outcrops, at which spontaneous burning and slumping often obscure the true thickness. Estimates of Fort Union lignite, to date, are based largely on outcrop data, because only limited drill hole information is available. Culbertson also believes that more detailed investigation is particularly likely to result in increase of the proved reserves lying under thin overburden and economically recoverable by surface mining methods.

Surface-Recoverable Reserves

Large-scale commercial mining of lignite in North Dakota and the rest of the Fort Union region is at present almost exclusively surface (strip) mining, and this is expected to continue to be the most economical mining method. Adequate data on total surface-recoverable reserves of the Fort Union formation are not available, but deposits lying close to the surface are known to be very extensive. Brant (4) has estimated that 70 percent of the reserves of North Dakota lignite, or nearly 250 billion tons, lies under 0 to 500 feet of overburden. Satisfactory data on lignite lying under economically strippable overburden, possibly 100 feet maximum, have not been developed, except in limited areas. However, the scattered information available makes it evident that eventual reserves in this category will be extremely large, running unquestionably into many billions of tons.

Constitution of Lignite

Chemical Composition

As outlined earlier, lignite is an arbitrarily defined subdivision of the continuous progression of coals, which extends from peat to anthracite and meta-anthracite. In the course of alteration of the original vegetable matter of which all coals and, hence, lignite are composed, water and volatile carbonaceous matter are lost, and the percentage of carbon is increased. Lignitic coal (brown coal and lignite) is the lowest rank of coal above peat, from which it is arbitrarily separated. Lignitic coal

3/ From a letter written in 1953.

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retains more chemical similarity to the original plant material than does coal of higher rank. For example, material of cellulosic nature and other carbohydrate complexes have been reported from lignitic coal (3). Evidence has also been presented that some of the original chemical differences between different plant parts are preserved in certain lignite deposits (3).

Lignitic coal is a very reactive organic substance. It combines so readily and actively with oxygen that storage in such a way as to prevent spontaneous combustion has been a serious problem in the past. (See section 6.) The reaction of lignite to many kinds of inorganic and organic solvents is greater than that of bituminous coal. For example, relatively mild oxidizing solutions, such as dilute hydrogen peroxide or sodium chlorite, will react with lignitic coal much more rapidly than with bituminous coal. Solutions of alkali that will scarcely affect bituminous coals will react instantly with many lignitic coals. Lignitic coal contains significant quantities of carbohydrates and carbohydrate derivatives. In bituminous coals condensation of chemical structure has greatly modified the nature of the carbon compounds.

Proximate and Ultimate Analysis

The analytical methods used by the Bureau of Mines (23) are followed by most other American laboratories. Briefly, proximate analysis consists of a determination of moisture released at 105° C., further matter volatile in a reducing atmosphere at 950° C., and ash residue at 700° to 750° C. Fixed carbon is calculated by difference. Conventional ultimate analysis is a determination of S, H, C, N, and ash, with oxygen being obtained by difference. Heat energy per pound is determined by combustion in a bomb calorimeter.

The same methods of analysis are used with lignitic coal as with other coals, with certain modifications, as explained by Fieldner and Selvig (23). Analytical procedures for volatile matter and for moisture are somewhat modified.

In the classification accepted in this country (1), lignitic coal has a heat-energy content of less than 8,300 B.t.u. per pound on the moist, mineral-matter-free basis. In this system of classification, the lower limit of lignitic coal - that is, its borderline with peat - has not been fixed. Lignitic coal that is unconsolidated is classified as brown coal and that consolidated is lignite. Subbituminous C coal, the rank just above lignite, has a B.t.u. content of more than 8,300 and less than 9,500 per pound on the moist, mineral-matter-free basis.

Analyses of Lignite and Other Coals

Table 2 lists proximate and ultimate analyses for samples of each common rank of coal. These analyses were selected as representative of each rank. The most important difference between lignite and the higher rank coals is the much higher moisture content of lignite. This high percentage of water exaggerates the difference between lignite and higher-rank coals for the various other constituents, expressed on the as-received basis.

Typical proximate analyses, and sulfur percentages, of lignite from various counties in North Dakota are listed in table 3, using data presented by Fieldner, Rice, and Moran (22). The range of B.t.u. per pound in table 3, 6,400 to 7,590, on the as-received basis, is general for lignite of the region, although examples well below 6,400 and somewhat above 7,590 occur.

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TABLE 2.--Proximate and ultimate analyses of samples of each rank of common banded coal of the United States, as-received basis

Rank or type	State	County	Proximate analysis				Ultimate analysis					Heating value	Source
			Moisture %	Volatile matter %	Fixed carbon %	Ash %	Sulfur %	Hydrogen %	Carbon %	Nitrogen %	Oxygen %	B.t.u./lb.	
Anthracite	Pennsylvania	Lackawanna	4.4	4.8	81.8	9.0	0.6	3.4	79.8	1.0	6.2	13,130	(11, p. 64)
Semianthracite	Arkansas	Pope	2.8	11.9	75.2	10.1	2.2	3.7	78.3	1.7	4.0	13,360	(18, p. 11)
Low-volatile bituminous	Maryland	Garrett	2.3	19.6	65.8	12.3	3.1	4.5	74.5	1.4	4.2	13,220	(38, p. 41)
Medium-volatile bituminous	Alabama	Jefferson	3.1	23.4	63.6	9.9	.8	4.9	76.7	1.5	6.2	13,530	(17, p. 24)
High-volatile A bituminous	Kentucky	Letcher	3.2	36.8	56.4	3.6	.6	5.6	79.4	1.6	9.2	14,090	(10, p. 114)
High-volatile B bituminous	Ohio	Muskingum	5.9	43.8	46.5	3.8	3.0	5.7	72.2	1.3	14.0	13,150	(19, p. 27)
High-volatile C bituminous	Illinois	Peoria	14.8	33.3	39.9	12.0	2.5	5.8	58.8	1.0	19.9	10,550	(9, p. 115)
Subbituminous A	Washington	King	13.9	34.2	41.0	10.9	.6	6.2	57.5	1.4	23.4	10,330	(20, p. 64)
Subbituminous B	Wyoming	Sheridan	22.2	32.2	40.3	4.3	.5	6.9	53.9	1.0	33.4	9,610	(21, p. 68)
Subbituminous C	Colorado	El Paso	25.8	31.1	38.4	4.7	.3	6.3	50.0	.6	38.1	8,580	(16, p. 64)
Lignite	North Dakota	Ward	36.8	27.8	30.2	5.2	.4	6.9	41.2	.7	45.6	6,960	(8, p. 52)

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TABLE 3. - Typical analyses of North Dakota lignite (as-received basis)[1/]

Item No.	County	Type of sample	Proximate analysis, percent				Sulfur percent	Heating value B.t.u.
			Moisture	Volatile matter	Fixed carbon	Ash		
1.....	Billings	D	38.0	25.8	29.4	6.8	0.6	7,010
2.....	Burleigh	D	31.9	30.2	31.8	6.1	.6	7,530
3.....	Divide	D	32.9	26.5	33.2	7.4	.5	7,590
4.....	McKenzie	D	41.9	24.2	28.4	5.5	.5	6,400
5.....	McLean	M	38.0	26.7	29.7	5.6	.4	6,710
6.....	Mercer	D	32.9	26.4	33.3	7.4	.8	7,320
7.....	Morton	M	35.6	28.9	27.9	7.6	1.4	7,020
8.....	Ward	D	35.1	26.5	30.0	8.4	.3	6,720
9.....	Williams	M	41.4	24.6	28.1	5.9	.9	6,600

D = delivered coal. M = mine sample.

1/ Bureau of Mines Bull. 446, 1942 (22).

Table 4 lists analyses by the Federal Bureau of Mines of samples collected at mine tipples in 15 North Dakota counties by official Bureau of Mines coal samplers. The table shows that North Dakota lignite is quite uniform in proximate and ultimate analyses. If analyses made on large lump sizes are compared, the uniformity is especially striking. The percentage of ash is greater in the smaller sizes.

The uniformity of the lignite mined from one bed is illustrated by the analyses listed in table 4 for the Truax-Traer Velva mine, Ward County. Analyses of the largest size, as sampled in 1942, 1946, and 1951, are remarkably alike. The heating values of the large sizes as reported in these three analyses are identical, within the limits of accuracy of the analytical procedures. The ash-softening temperature also indicates uniformity of the bed (Coteau bed).

Tipple samples give analytical values for the average product of a mine. This tends to be uniform, especially if one thick bed is mined. Parts of a bed at varying distances from the bottom of the seam may show marked chemical differences, however. Analysis of samples taken from approximately 4-inch vertical consecutive segments from 1 column of lignite from the Beulah-Zap bed at the Dakota Collieries mine, Zap, Mercer County, N. Dak., showed variation in heating value from 6,540 to 7,720 B.t.u. per pound, on the as-received basis.[4/] This variation is of the same order as that for lignite from all parts of the Fort Union region. The value for the column sample as a whole is 7,180 B.t.u.

Analyses of lignite from Arkansas, Texas, California, Montana, and South Dakota are listed in table 5. The Montana and South Dakota lignites are from the Fort Union region and, as would be expected, the analyses are very much like those listed in tables 3 and 4 for North Dakota. Even the Arkansas, Texas, and California lignites show relatively small differences from Fort Union lignite. Yet the lignites of California and of the Gulf province are quite different from the lignite of the Fort Union region in determinable physical structure and chemical nature. This is shown by microscopic study and by simple chemical studies, such as carbonization assay or extraction with commonly used solvents (34, 37).

4/ From data compiled by the Bureau of Mines, Grand Forks, N. Dak.

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TABLE 4.—Analyses of North Dakota lignite

Item No.	County	Town	Mine	Bed 1/	Size of coal	Tons sampled (approx.)	Type of sample	Proximate analysis, percent: Moisture (as-recd. basis)	Proximate analysis, percent: Moisture-free basis: Volatile matter	Fixed carbon	Ash	Ultimate analysis, percent: Moisture-free basis: Sulfur	Hydrogen	Carbon	Nitrogen	Oxygen	B.t.u./lb. (as-recd. basis)	B.t.u./lb. (moisture-free basis)	Ash softening temp., °F.	Date of sampling	Source
1	Adams	Haynes	Arrowhead	Haynes	3" lump	75	T	35.4	42.2	44.5	13.3	1.6	4.3	63.3	0.8	16.7	6,960	10,780	2190	2-17-51	2/, p. 44
2	Do	do.	do.	do.	2" lump	80	T	33.5	41.2	43.0	15.8	1.9					7,000	10,530	2130	10-18-51	3/
3	Do.	do.	do.	do.	2" x 3/8"	60	T	32.3	40.7	39.2	20.1	2.1					6,790	10,030	2180	10-18-51	3/
4	Do.	do.	do.	do.	-3/8"	20	T	32.7	38.4	36.9	24.7	2.2					6,320	9,400	2180	10-18-51	3/
5	Do.	do.	Pearl Butte	do.	1-1/2" lump	8	T	36.5	44.2	44.6	11.2	1.7	4.7	65.6	.9	15.9	7,230	11,390	2340	2-21-47	2/, p. 44
6	Do.	do.	do.	do.	-1-1/2"	1	T	35.5	45.1	41.9	13.0	2.1					7,190	11,140	2290	2-21-47	2/, p. 44
7	Bowman	Bowman	Twin Buttes		Run of mine	5	T	48.3	46.5	43.0	10.5	1.7	4.5	63.9	.9	18.5	5,660	10,940	2470	12-21-46	2/, p. 45
8	Do.	Gascoyne	Peerless	Harmon	-2"	600	T	43.1	43.0	44.6	12.4	1.4					6,110	10,740	2360	10-17-51	3/
9	Do.	do.	do.	do.	-8" x 2"	50	T	43.7	43.1	45.6	11.3	1.4					6,070	10,780	2500	10-17-51	3/
10	Burke	Columbus	Kincaid	Noonan	1/4" x 8"	120	T	36.1	40.6	50.6	8.8	.6	4.4	66.4	1.0	18.8	7,180	11,230	2190	10-30-46	2/, p. 45
11	Do.	do.	do.	do.	8" x 5"	250	T	36.7	42.9	48.7	8.4	.5					7,100	11,200	2160	9-28-51	3/
12	Do.	do.	do.	do.	5" x 2"	300	T	36.4	42.1	48.4	9.5	.5					7,080	11,130	2080	9-28-51	3/
13	Do.	do.	do.	do.	2" x 1/2"	125	T	36.1	40.0	46.6	13.4	.5					6,780	10,610	2100	9-28-51	3/
14	Do.	do.	do.	do.	-1/2"	75	T	38.1	38.7	45.8	15.5	.7					6,430	10,390	2070	9-28-51	3/
15	Burleigh	Wilton	Burleigh	Wilton	8" lump	70	T	41.7	45.3	46.7	8.0	1.1	4.6	65.8	.8	19.7	6,510	11,170	2440	12-17-42	4/, p. 42
16	Do.	do.	do.	do.	8" x 4"	70	T	40.9	45.7	45.9	8.4	.9					6,580	11,120	2440	12-17-42	4/, p. 42
17	Do.	do.	do.	do.	3" x 2"	70	T	40.9	44.5	45.7	9.8	1.0					6,440	10,990	2390	12-17-42	4/, p. 42
18	Do.	do.	do.	do.	1 1/2" x 1/2"	70	T	40.7	44.5	45.6	9.9	1.0					6,490	10,960	2350	12-17-42	4/, p. 42
19	Do.	do.	do.	do.	2" slack	70	T	41.1	43.9	44.2	11.9	1.0					6,270	10,650	2270	12-17-42	4/, p. 42
20	Do.	do.	Backman		Run of mine	5	T	40.1	45.8	45.8	8.4	1.0	4.5	65.6	.9	19.6	6,660	11,110	2540	1-28-47	2/, p. 45
21	Do.	do.	Ecklund	Wilton	do.	8	T	39.9	44.7	43.2	12.1	1.3	4.4	63.6	1.0	17.6	6,480	10,790	2390	1-27-47	2/, p. 45
22	Divide	Noonan	Beukol-Noonan	Noonan	15" x 3"	500	T	34.3	41.6	50.5	7.9	.6	4.4	66.8	1.2	19.1	7,430	11,300	2340	10-31-46	2/, p. 45
23	Do.	do.	do.	do.	12" x 4"	300	T	35.7	41.5	50.5	8.0	.4					7,360	11,460	2420	9-21-51	3/
24	Do.	do.	do.	do.	4" x 3"	50	T	35.7	42.5	49.3	8.2	.5					7,310	11,380	2520	9-21-51	3/
25	Do.	do.	do.	do.	3" x 2"	50	T	34.2	42.7	48.8	8.5	.5					7,360	11,360	2520	9-21-51	3/
26	Do.	do.	do.	do.	-2"	350	T	35.5	42.5	47.8	9.7	.6					7,210	11,180	2420	9-21-51	3/
27	Do.	do.	do.	do.	-1/4"	80	T	36.2	39.5	47.0	13.5	.9					6,890	10,790	2130	9-21-51	3/
28	Dunn	Dunn Center	Pelton	Dunn Center	2" lump	25	T	42.8	45.2	47.0	7.8	.7					6,350	11,090	2530	10-11-51	3/
29	Do.	do.	do.	do.	2" x 1/2"	8	T	43.8	43.7	45.1	11.2	1.4					6,130	10,890	2520	10-11-51	3/
30	Do.	do.	do.	do.	-1/2"	2	T	46.3	44.1	45.1	10.8	1.1					5,870	10,930	2580	10-11-51	3/
31	Grant	New Leipzig	Davenport	Haynes	1-1/4" lump	90	T	35.2	43.1	45.3	11.6	1.5					7,040	10,860	2470	10-19-51	3/
32	Do.	do.	do.	do.	-1-1/4"	10	T	33.1	38.6	37.4	24.0	2.8					6,210	9,290	2100	10-19-51	3/
33	McLean	Garrison	Custer	Garrison Creek	Run of mine	500	T	39.5	42.9	48.2	7.9	.6					6,700	11,060	2510	2- 5-47	2/, p. 45
34	Do.	do.	do.	do.	5" lump	50	T	39.5	45.1	48.6	6.3	.6	4.6	66.6	1.1	20.8	6,810	11,250	2580	2- 5-47	2/, p. 45
35	Do.	do.	do.	do.	12" x 7"	275	T	38.7	45.3	48.2	6.5	.5					6,910	11,270	2420	10- 8-51	3/
36	Do.	do.	do.	do.	7" x 2"	420	T	38.4	44.4	47.2	8.4	.6					6,860	11,130	2570	10- 8-51	3/
37	Do.	do.	do.	do.	-2"	700	T	38.5	43.5	44.5	12.0	.6					6,510	10,590	2340	10- 8-51	3/
38	Do.	Underwood	Underwood	Stanton	12" x 6"	7	T	38.9	44.6	47.9	7.5	.6					6,820	11,170	2470	10- 9-51	3/
39	Do.	do.	do.	do.	6" x 3"	30	T	39.3	44.2	47.6	8.2	.9					6,720	11,070	2470	10- 9-51	3/
40	Do.	do.	do.	do.	3" x 2"	10	T	38.5	44.6	44.7	10.7	1.1					6,620	10,780	2470	10- 9-51	3/
41	Do.	do.	do.	do.	2" x 3/4"	15	T	38.5	44.0	44.3	11.7	1.0					6,570	10,680	2430	10- 9-51	3/
42	Do.	do.	do.	do.	-3/4"	10	T	38.9	41.3	44.0	14.7	.9					6,260	10,250	2180	10- 9-51	3/
43	Do.	do.	Figenskau		4" lump	15	T	41.0	45.3	46.7	8.0	.8	4.5	65.6	1.0	20.1	6,610	11,200	2580	2-10-47	2/, p. 45
44	Do.	do.	do.		4" x 1-1/2"	10	T	40.2	45.0	45.3	9.7	.8					6,600	11,040	2230	2-10-47	2/, p. 45
45	Do.	do.	do.		1-1/2" x 1/2"	5	T	39.9	44.6	44.3	11.1	.9					6,570	10,920	2360	2-10-47	2/, p. 45
46	Do.	do.	do.		-1/2"	5	T	40.1	43.0	42.2	14.8	.9					6,210	10,380	2180	2-10-47	2/, p. 45
47	Mercer	Beulah	Knife River	Beulah-Zap	12" x 4"	125	T	36.3	42.5	48.8	8.7	1.1					7,090	11,120	2590	10-11-51	3/
48	Do.	do.	do.	do.	4" x 2"	50	T	35.8	40.6	48.4	11.0	1.1					6,890	10,740	2360	10-11-51	3/
49	Do.	do.	do.	do.	2" x 1"	40	T	34.9	41.9	44.8	13.3	2.0					6,890	10,580	2360	10-11-51	3/
50	Do.	do.	do.	do.	-1"	120	T	35.3	41.5	45.4	13.1	1.3					6,830	10,560	2420	10-11-51	3/
51	Do.	do.	do.	do.	10" x 4"	600	T	37.3	40.9	49.1	10.0	1.3					6,930	11,060	2470	11-25-52	3/
52	Do.	do.	do.	do.	4" x 2"	100	T	35.7	42.1	47.1	10.8	1.1					7,010	10,900	2450	11-25-52	3/
53	Do.	do.	do.	do.	2" x 1"	100	T	35.2	40.5	46.9	12.6	1.6					6,970	10,750	2230	11-25-52	3/
54	Do.	do.	do.	do.	-1"	200	T	35.7	39.8	46.6	13.6	1.4					6,800	10,580	2140	11-25-52	3/
55	Do.	do.	do.	do.	-2"	250	T	36.4	40.8	48.2	11.0	1.2					6,960	10,950	2300	11-25-52	3/
56	Do.	Hazen	Dakota Star	do.	10" x 4"	1000	T	36.0	42.7	49.1	8.2	.9					7,150	11,160	2500	11-26-52	3/
57	Do.	do.	do.	do.	10" x 2" crushed to -2"	600	T	36.8	43.7	48.6	7.7	.8					7,060	11,180	2520	11-26-52	3/
58	Do.	do.	do.	do.	R/m crushed to -2"	1800	T	36.5	44.4	46.8	8.8	.9					7,040	11,090	2490	11-26-52	3/
59	Do.	do.	do.	do.	6" x 4"	50	T	37.4	44.0	48.9	7.1	.8	4.5	66.3	.9	20.4	6,980	11,210	2000	2-12-47	2/, p. 45
60	Do.	do.	do.	do.	1-1/2" x 1/2"	50	T	37.4	41.9	48.4	9.7	1.1					6,950	11,100	2380	2-12-47	2/, p. 45
61	Do.	do.	do.	do.	-1"	400	T	37.3	43.3	47.4	9.3	.7					6,970	11,120	2390	2-12-47	2/, p. 45
62	Do.	Zap	Indian Head	do.	6" x 3"	350	T	35.9	42.6	47.8	9.6	1.2	4.3	65.9	.9	18.1	7,140	11,130	2260	2-15-47	2/, p. 45
63	Do.	do.	do.	do.	1-1/2" x 3/8"	80	T	35.6	42.4	47.3	10.3	1.0					7,120	11,060	2190	2-15-47	2/, p. 45
64	Do.	do.	do.	do.	Modified -1-1/2"	200	T	35.9	41.2	47.6	11.2	1.0					7,000	10,920	2200	2-15-47	2/, p. 45
65	Do.	do.	do.	do.	8" x 3 1/2" lump	250	T	35.9	43.4	48.2	8.4	.8					7,180	11,190	2500	11-21-52	3/
66	Do.	do.	do.	do.	1-1/2" x 3/4"	120	T	34.8	43.1	47.5	9.4	.9					7,210	11,050	2490	11-21-52	3/
67	Do.	do.	do.	do.	-2"	550	T	35.2	42.0	46.6	11.4	.9					7,040	10,860	2360	11-21-52	3/

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TABLE 4.—Analyses of North Dakota lignite (continued)

Item No.	County	Town	Mine	Bed 1/	Size of coal	Tons sampled (approx.)	Type of sample	Proximate analysis, percent: Moisture (as recd. basis)	Proximate analysis, percent: Moisture-free basis: Volatile matter	Fixed Carbon	Ash	Ultimate analysis, percent: Moisture-free basis: Sulfur	Hydrogen	Carbon	Nitrogen	Oxygen	B.t.u./lb. (as recd. basis)	B.t.u./lb. (moisture-free basis)	Ash softening temp., °F.	Date of sampling	Source
68	Morton	Glen Ullin	Richter	E	1-1/4" lump	20	T	42.1	43.6	45.8	10.6	1.8	4.4	64.4	1.1	17.7	6,300	10,880	2490	2-13-47	2/, p. 45
69	Do.	do.	do.	E	1-1/4" x 1/4"	5	T	40.4	41.0	39.6	19.4	1.8					5,840	9,800	2500	2-13-47	2/, p. 45
70	Do.	do.	do.	E	-1/4"	1	T	41.0	35.6	32.7	31.7	1.3					4,720	7,990	2100	2-13-47	2/, p. 45
71	Do.	New Salem	Flemmer	I	+2" lump	30	T	40.0	44.3	48.1	7.6	1.0	4.5	65.6	1.1	20.2	6,640	11,080	2600	10-11-51	3/
72	Do.	do.	do.	I	2" x 1/2"	8	T	39.5	43.3	45.4	11.3	1.6					6,490	10,720	2310	10-11-51	3/
73	Do.	do.	do.	I	-1/2"	2	T	39.0	41.6	43.3	15.1	1.4					6,250	10,240	2160	10-11-51	3/
74	Mountrail	White Earth	Tinmel	3	2" lump	25	T	43.1	42.0	51.6	6.4	.4	4.4	66.9	1.2	20.7	6,430	11,310	2420	11- 7-46	3/, p. 45
75	Oliver	Center	Hagel	E?	1-1/2" lump	40	T	37.7	42.6	48.4	9.0						6,910	11,090	2470	10-12-51	3/
76	Do.	do.	do.	do.	1-1/2" x 3/8"	8	T	36.0	42.0	44.7	13.3						6,750	10,550	2150	10-12-51	3/
77	Do.	do.	do.	do.	-3/8"	2	T	35.2	39.2	44.0	16.8						6,540	10,090	2100	10-12-51	3/
78	Stark	Dickinson	Lehigh	E or F			Mine	41.2	43.3	45.6	11.1	.9	4.6	63.9	.9	18.6	6,340	10,790	2140	5-23-42	4/, p. 48
79	Ward	Velva	Velva	Coteau	8" x 4"	300	T	39.2	44.2	50.0	5.8	.3	4.6	67.0	.9	21.4	6,840	11,260	2550	10- 2-42	4/, p. 54
80	Do.	do.	do.	do.	4" x 2"	200	T	39.3	43.2	49.6	7.2	.3					6,740	11,100	2580	10- 2-42	4/, p. 54
81	Do.	do.	do.	do.	2" x 1/2"	130	T	39.4	42.3	49.4	8.3	.2					6,620	10,940	2550	10- 2-42	4/, p. 54
82	Do.	do.	do.	do.	-1/2"	70	T	40.4	40.8	48.7	10.5	.8					6,420	10,770	2480	10- 2-42	4/, p. 54
83	Do.	do.	do.	do.	8" x 6"	400	T	39.2	45.1	48.2	6.7	.4					6,810	11,200	2570	10-12-51	3/
84	Do.	do.	do.	do.	6" x 2"	500	T	38.8	44.3	46.9	8.8	.4					6,690	10,940	2570	10-12-51	3/
85	Do.	do.	do.	do.	-2"	600	T	39.6	41.2	45.8	13.0	.7					6,270	10,380	2260	10-12-51	3/
86	Do.	do.	do.	do.	8" x 4"	450	T	39.1	43.9	49.8	6.3	.4	4.5	66.1	.9	21.8	6,810	11,180	2560	10-25-46	3/, p. 46
87	Do.	do.	do.	do.	4" x 3"	100	T	39.1	43.6	49.4	7.0	.3					6,760	11,090	2530	10-25-46	3/, p. 46
88	Do.	do.	do.	do.	3" x 2"	160	T	38.6	43.3	48.5	8.2	.3					6,720	10,940	2520	10-25-46	3/, p. 46
89	Do.	do.	do.	do.	2" x 1/2"	160	T	38.5	43.3	47.4	9.3	.3					6,660	10,830	2450	10-25-46	3/, p. 46
90	Do.	do.	do.	do.	-1/2"	120	T	39.9	41.1	46.9	12.0	.7					6,340	10,560	2260	10-25-46	3/, p. 46
91	Do.	Sawyer	Miller	do.	12" x 2"	50	T	39.1	43.2	50.2	6.6	.3					6,760	11,100	2490	10- 4-51	3/
92	Do.	do.	do.	do.	2" x 1/4"	15	T	38.8	40.0	50.5	9.5	.3					6,500	10,620	2540	10- 4-51	3/
93	Do.	do.	do.	do.	-1-1/4"	10	T	39.1	39.1	48.2	12.7	.3					6,210	10,200	2470	10- 4-51	3/
94	Williams	Tioga	M and M	B?	8" lump	20	T	41.7	44.0	47.7	8.3	.7	4.5	65.6	1.1	19.8	6,530	11,190	2530	11- 7-46	3/
95	Do.	do.	do.	do.	8" x 4"	5	T	41.8	42.7	47.5	9.8	.6					6,420	11,020	2380	11- 7-46	3/
96	Do.	do.	do.	do.	4" x 1-1/2"	5	T	41.0	42.3	46.5	11.2	.6					6,390	10,840	2180	11- 7-46	3/
97	Do.	do.	do.	do.	1-1/2" x 1/2"	5	T	41.4	41.2	44.0	14.8	.7					6,080	10,380	2230	11- 7-46	3/
98	Do.	do.	do.	do.	-1/2"	5	T	42.6	40.1	42.7	17.2	.9					5,810	10,130	2220	11- 7-46	3/

1/ Bed identifications from U. S. Geol. Survey Circ. 226 (4).
2/ Bureau of Mines Bull. 516 (28).
3/ Unpublished Fuel Inspection data, Bureau of Mines, Grand Forks, N. Dak.
4/ Bureau of Mines Tech. Paper 700 (8).

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TABLE 5.--Analyses of U. S. lignites from states other than North Dakota, as-received basis

State	County	Mine	Type of sample	Proximate analysis, percent				Ultimate analysis, percent					B.t.u./lb.	Source
				Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	Hydrogen	Carbon	Nitrogen	Oxygen		
Montana	Sheridan	Acme	1-1/2" lump	39.0	25.1	30.2	5.7	0.5	7.0	40.2	0.7	45.9	6,810	1/, p. 23
South Dakota	Harding			41.0	23.2	28.4	7.4	2.2	7.0	37.8	.5	45.1	6,380	2/
Arkansas	Dallas	American Dyewood Co	Face	34.5	31.8	23.5	10.2	.4	7.1	39.7	.7	41.9	6,950	1/, p. 22
	Hot Springs	Outcrop	Face	38.9	29.1	19.7	12.3	.8	7.5	34.6	.4	44.4	6,260	1/, p. 22
	Ouachita	Dunn	Face	37.5	32.4	21.6	8.5	.4	7.5	39.9	.6	43.1	7,080	1/, p. 22
Texas	Milam	Sandow	Face	31.9	29.3	27.9	10.9	1.7	6.5	41.5	.8	38.6	7,150	1/, p. 24
	Milam	Sandow	Face	33.2	29.3	29.8	7.7	1.3	6.8	43.4	.8	40.0	7,510	1/, p. 24
California	Amador	American Lignite Products Co	Column	36.8	36.8	16.2	10.2	1.0	8.0	38.2	.4	42.2	7,060	1/, p. 22
	Amador	Edwin No. 2 Clay	Face	37.3	32.9	21.4	8.4	1.0	7.2	36.0	.4	47.0	6,280	1/, p. 23

1/ U. S. Bureau of Mines Bulletin 482 (37).
2/ Davis, J. D. and Galloway, A. E. (13).

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Mineral Matter and Ash of Fort Union Lignite

Mineral or inorganic matter is always present in coal, as would be expected because fresh plant material of the sort that contributes to peat contains about 0.1 to 3 percent mineral matter. This is the so-called inherent mineral matter of coal - inorganic compounds contained in the original plant substance. Different plant parts differ markedly in percentage of mineral matter. Wood ordinarily contains less than 1 percent ash, averaging about 0.5 percent of the dry wood. Wood is about 40 percent water, so the ash is about 0.3 percent of the fresh wood (25). Richter (31) found the fresh bark of 7 common American lumber trees to be 1.5 to 8.3 percent ash, with a mean of 3.6 percent, in other words, many times as great as the ash content of wood. Some other plant parts have even higher mineral matter content. Some plants selectively concentrate certain minerals; for example, Equisetum concentrates silica.

Analysis of many American peats shows that the raw peat has an ash content of about 2.5 percent (mean figure obtained from analyses listed by Davis (12, pp. 186-203), eliminating the peats with more than 10 percent ash, which apparently was largely inorganic silt. Peats with less than 70 percent moisture were also rejected because they were apparently partly dried, hence not raw peat. It is evident that this is fairly close to the percentage for raw plant material. Of the dry peat in the same analyses, about 12 percent is ash, eliminating the relatively few peats that had more than 20 percent ash on the dry basis. Most of these were apparently composed largely of inorganic silt. This figure may be compared with 8.8 percent, the average percentage of ash on the dry basis for the coals of all ranks listed in table 2. The range of percentage of ash in the dry coal is 3.7 to 14. Although some changes, both in composition and quantity of mineral matter, occur in the process of coal formation from peat, there is little reason to believe that the changes are, on the whole, very large. The major concentration of mineral matter occurs primarily in the process of converting fresh plant material to peat; that is, sedimentation. Fort Union lignite contains about 8 to 9 percent ash on the dry basis, probably very near the ash content of the original peat. Sprunk and O'Donnell (39) list four samples of pure anthraxylon (petrographic term for wood and some other plant tissues in coal) from North Dakota lignite as ranging from 2.8 to 4.0 percent ash, on the as-received basis. A sample of anthraxylon (pure wood in this instance) collected from a fresh lignite face in the Truax-Traer Velva mine in 1952 contained 2.5 percent ash on the as-received basis and only 4.6 percent on the dry coal basis.5/ This is rather near the probable inherent ash figure for the living plant substance and suggests that a relatively large part of the ash in North Dakota lignite is in the nonanthraxylous (essentially equivalent to nonwoody) fraction.

In the formation of peat, a number of processes affecting the mineral-matter content operate: There is probably removal by leaching of some of the inherent mineral matter, and there is certainly the addition of mineral matter to the vegetable substances. This added mineral matter is sometimes called extraneous mineral matter to contrast it with the inherent or original inorganic part of the plant material. Some of this extraneous mineral matter is erosional detritus - especially sand (silica) and clay (kaolin and other clay minerals). This sort of mineral matter is often mixed with peat rather intimately. As the percentage of clay, for example, rises, the coal containing it approaches or may become a carbonaceous shale. If the deposition of relatively pure peat is temporarily interrupted by deposition of quantities of clay or sand, the result is a parting between benches of the coal bed. Such partings are a handicap in mining. They do occur in beds of Fort Union lignite but fortunately are not the rule.

5/ From data compiled by the Bureau of Mines, Grand Forks, N. Dak.

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Other extraneous mineral matter has been precipitated from solution into cracks and spaces in the coal after formation of peat was well advanced or even after formation of the coal beds. In Fort Union lignite, gypsum (selenite) and iron pyrite are the most abundant minerals of this sort. Calcite also occurs. At some locations in the Harmon lignite bed (Bowman County, N. Dak.) selenite crystals up to 5 inches long are very abundant. The calcite and gypsum presumably owe their origin to factors of solubility and crystal formation. The pyrite, on the other hand, perhaps was precipitated by action of microorganisms. Certain bacteria, for example, in the course of their physiological processes can cause precipitation of iron sulfide from solutions containing sulfur and iron (27). Pyrite and other extraneous mineral matter may occur as finely disseminated crystals or in sizable concretions in Fort Union lignite. Some crystals of pyrite in North Dakota lignite are visible only in microscopic examination or may in some instances be detected only in X-ray diffraction analysis. Pyritic nodules an inch or more in diameter also occur. In many places in the Fort Union region, concretions called sulfur balls, which range from about 1 inch to 6 or more inches in diameter are found in the lignite beds. Examples of these sulfur balls from the Knife River mine, Beulah, Mercer County, N. Dak., are shown in figure 8. They are composed primarily of gypsum, iron pyrite, and fragments of lignite.

Ash Versus Mineral Matter. - When coal or other organic material is burned, a residue, largely of mineral matter, remains. It will be noted that, in speaking of percentage composition above, ash and mineral matter were used as essentially equivalent; that is, the percentage of ash in a substance was taken to be equivalent to the percentage of mineral matter in the substance. This is not strictly true because the process of heating and oxidation volatilizes some inorganic compounds (minerals) and oxidizes others, changing their weight. Perhaps more important, the process of ashing coal changes the chemical nature of the mineral matter so that analyses of ash composition do not show the true composition of the mineral matter in the coal. For example, pyrite, a characteristic component of Fort Union lignite, is oxidized on ashing to volatile oxides of sulfur and an iron oxide residue. The best technique known for studying the exact composition of mineral matter is probably X-ray diffraction analysis, although petrographic analysis with a microscope is satisfactory where crystals of large enough size exist. Either of these methods permits study of the original mineral matter. X-ray diffraction analysis can detect very small quantities of mineral matter, but satisfactory results with lignite demand either very long exposures with whole lignite or some physical method of concentration of the mineral matter (for example, float-and-sink techniques), because the organic mass of the lignite has a strong dilution effect (51).

However, detailed ash-composition data do provide in part the basis for estimating original mineral constituents. In addition, the composition and consequent chemical and physical characteristics of coal ash as such are of considerable importance in coal utilization.

The ash characteristic most commonly determined for utilization purposes is the ash-softening temperature. Coal-ash analyses report a softening temperature at which cones of specially prepared ash soften and flow down to a spherical lump in a reducing atmosphere (23). This gives an estimate of the temperature at which ash from the coal may be expected to soften and clinker in the fuel bed of a furnace. Table 6 lists the range of ash-softening temperatures of a representative group of 69 North Dakota lignites, as presented by Snyder and Aresco (38). The range is 2,000° to 2,600° F. Ranges of ash-softening temperature for other coal ranks and mining areas are also listed in table 6 for comparison. Analyses, including ash-softening temperature, for 98 lignite samples are listed in table 4. The range of ash-softening temperature is 2,000° to 2,690° F., with a mean of 2,380° F.

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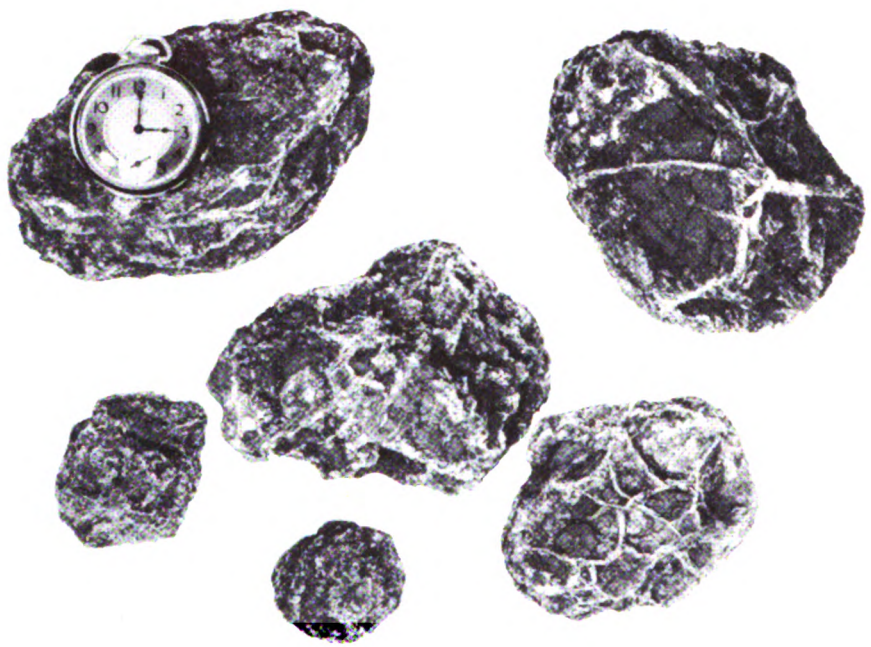

Figure 8. - Sulfur balls.

Collected at the tipple of the Knife River Coal Mining Co., Beulah mine, Beulah, Mercer County, N. Dak., in July 1951. These occur commonly in the lignite bed and are composed of gypsum, iron pyrite, and lignite.

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TABLE 6. - Usual range of ash-softening temperatures for coals of various rank

	Ash-softening temperature, °F.		
	Low	High	Reference
Anthracite (Pa.).....	2,300	2,900+	(8, pp. 22-23)
Bituminous (Pa.):			
Hva[1].....	2,400	2,700	(8, pp. 32-33)
Hva.....	2,100	2,700	Do.
Lv.....	2,200	2,800	(8, pp. 34-35)
Mv.....	2,200	2,800	Do.
Bituminous (Ill.):			
Hvb.....	2,100	2,500	(8, pp. 18-19)
Hvc.....	2,000	2,300	(8, pp. 20-21)
Bituminous (Ky.):			
Hva.....	2,100	2,300	(8, pp. 22-23)
Hva.....	2,200	2,700	Do.
Hvb.....	2,000	2,100	Do.
Hva.....	2,600	2,900	Do.
Subbituminous (Wyo.):			
Subb.....	2,100	2,300	(8, pp. 44-45)
Subb.....	2,100	2,500	Do.
Lignite (N. Dak.):			
Lignite.....	[2]2,000	2,600	(18, pp. 45-46)

1/ Hva: High volatile A. Hvb: High volatile B. Hvc: High volatile C. Lv: Low volatile. Mv: Medium volatile. Subb: Subbituminous B.
2/ Range of 69 samples.

Table 7 lists analyses of the major constituents in the ash from a number of North Central lignites.[6] A more complete analysis of the composition of ash from a single North Dakota lignite derived from Dickinson lignite char is given in table 8. The range of analyses presented in table 7 is listed in table 9, with comparative data on the range of principal ash constituents for United States coals as a whole. The data in table 9 indicate that the ash of North Dakota lignite is relatively high in percentage of calcium and magnesium oxides. This has been attributed by Roe (32) to the mineral matter contained by the original plant substance of the lignite. Older coals have more alumina and silica in their ash, which is thought by Roe to be due to the higher content of aluminum and silicon in the extinct forms of plants that contributed to the older coals. Others have held the opinion that the solute content of the water in the original site of deposition is the important factor; see, for example, White and Thiessen (50).

6/ From data compiled by the Bureau of Mines, Grand Parks, N. Dak.

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TABLE 7. - Composition of ash from various Fort Union lignites, percent[1/ 2/]

Lignite	SiO_2	Al_2O_3[3/]	Fe_2O_3	CaO	MgO	SO_3	Na_2O+K_2O	Ash-softening temperature, °F.
Truax-Traer Kincaid mine, Burke County, N. Dak.	28.0	19.8	6.6	16.5	3.3	14.9	10.6	2,150
Baukol-Noonan mine, Divide County, N. Dak.	30.4	15.4	8.5	16.5	4.8	15.2	8.9	2,150
Dakota Collieries Zap mine, Mercer County, N. Dak.	17.5	9.9	15.0	17.8	5.6	28.3	5.8	2,290
Knife River Coal Mining Co. mine, Beulah, Mercer County, N. Dak.	23.1	12.3	8.7	18.8	7.3	24.8	4.8	2,340
Dakota Briquets and Tar Products, Inc., mine, Dickinson, Stark County, N. Dak.	11.2	8.3	29.8	18.6	4.9	26.2	.6	2,400
Truax-Traer Custer mine, McLean County, N. Dak.	18.1	10.7	6.4	32.7	7.8	17.9	6.0	2,570
Western Dominion mines, Ltd., Bienfait mine, Bienfait, Saskatchewan, Canada	16.0	15.0	6.1	29.9	7.6	18.5	6.6	2,570

1/ Lignite samples taken by periodic sampling from carloads of delivered stoker-size coal, rescreened to 3/8 by 1-1/2 inch.
2/ Loss on ignition at 800° C. varied from 0.1 to 0.4 percent.
3/ Al_2O_3 includes any titanium oxide or phosphorus pentoxide that may be present.

TABLE 8. - Composition of ash from lignite char[1/]

Constituent	Ash ignited at 800° C., percent	Constituent	Ash ignited at 800° C., percent
SiO_2	20.71	Cl	0.124
TiO_2	.67	B_2O_3	.67
Al_2O_3	9.96	BaO	.166
Fe_2O_3	5.41	CuO	.025
MnO	.19	ZnO	.05
CaO	25.60	Bi_2O_3	Trace
MgO	9.82	V_2O_5	Absent
Na_2O	2.91	Summation	99.79
K_2O	.44	Less O for Cl	.03
SO_3	23.00	True total	99.76
P_2O_5	.043		

1/ Dickinson, Stark County, N. Dak. (5).

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TABLE 9. - Comparison of ash composition for all United States coals and for North Dakota lignite, percent

Constituent	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	Na_2O+K_2O	SO_3
Usual range all United States coals, percent 1/	20-60	10-35	5-35	1-20	0.3-4.0	0.5-2.5	1-4	0.1-12
Range N. Dak. lignite, percent 2/	11-30	8-20	6-30	17-33	3.3-7.8	(3)	0.6-10.6	15-28
Average N. Dak. lignite, percent 2/	21.4	12.7	12.5	20.2	5.6	(3)	6.1	21.2

1/ Bureau of Mines Tech. Paper 679 (35).
2/ Based on data of table 7.
3/ Al_2O_3 includes any titanium oxide or phosphorus pentoxide that may be present.

There is also considerable evidence that the mineral matter of lignite sometimes includes small quantities of uncommon or rare elements and minerals that may be recoverable commercially. The nature of the occurrence of the rare elements in lignite is being investigated in several laboratories in this country. Here again the question of inherent versus extraneous mineral matter is important. Plants exist that are able to concentrate uncommon and rare elements to proportions many times their abundance in the soil in which the plants grow. Some concentrations of rare elements in lignite may be due to concentration of the elements in the original plant material. Secondary enrichment of the coal substance by solutions bearing rare elements is probably responsible in other instances. Gott, Wyant, and Beroni (26) believe that uranium in Fort Union lignite existed in the original peat but do not state whether they believe the element to have been in the plant material itself or in the form of extraneous mineral matter. Stadnichenko, Murata, and Axelrod (41) reported investigation of lignite from the Cretaceous Patuxent formation (District of Columbia and vicinity), the ash of which contains up to 6.0 percent germanium, 0.7 to 5.0 percent vanadium, 0.1 to 0.8 percent chromium, and 0.03 to 0.2 percent gallium. In a more recent paper Stadnichenko, Murata, Zubovic, and Hufschmidt (42) note that lignitic logs of Cretaceous age in the Atlantic coastal plain contain as much as 7.5 percent germanium in the ash. In the same paper, ash of Fort Union coals from Wyoming (subbituminous), North Dakota (lignitic), and Montana (subbituminous and lignitic) were reported as containing varying amounts of germanium. Most of these coals contained negligible amounts of germanium, but the ash of part of one subbituminous coal bed was as much as 4.7 percent germanium (Tongue River member of the Fort Union formation; Klein No. 2 mine, Republic coal Co., Klein, Musselshell County, Mont.). Deul and Annell (14) analyzed low-rank coal ash from several parts of the United States, including Fort Union lignites from North and South Dakota. In most areas from which coal ash was studied, boron, barium, silicon, lead, titanium, phosphorus, and manganese were found to be present in the ash in concentrations as high as 0.1 - 1.0 percent. Arsenic, vanadium, molybdenum, zirconium, zinc, nickel, cobalt, beryllium, and yttrium were found in similar concentrations in lignite ash from some of the areas studied. Copper, chromium, scandium, gallium, germanium, lithium, and lanthanum were found in concentrations up to 0.01 to 0.1 percent. Ytterbium was present in certain of the lignite ashes studied at a concentration of 0.001 to 0.01 percent of the ash. The authors note that lead, tin, strontium, molybdenum, cobalt, boron, and lanthanum were found in unusually high concentration in many instances.

Uranium exists in various American coals, mostly western low-rank coals. The greatest number of known localities of uraniferous coals are in the Fort Union lignite region - in northwestern South Dakota, southwestern North Dakota, and adjacent

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eastern Montana (26). Some Fort Union coal in Wyoming also contains uranium. Gott, Wyant, and Beroni (26) state that in the lignite of the Fort Union region the greatest concentration of uranium is in the coal at the top of the Paleocene. Presumably they refer to the Sentinel Butte and Tongue River members of the Fort Union formation.

Petrography and Paleobotany of Fort Union Lignite

The study of the observable physical structure of coal, both megascopic and microscopic, is usually called either paleobotany or coal petrography, depending on techniques and emphasis of the investigation. If coal is considered primarily as a sedimentary rock and features are classified and recorded in terms of the nature of structural constituents that are apparently different megascopically, microscopically, or both, the term coal petrography is conventionally used to describe the study. If coal is studied with its vegetable origin foremost in mind and structural features interpreted as more or less altered features of the original plant material, the methods are those of paleobotany. In practice, these two contrasting points of view have been rather completely fused in the development of this branch of science. Those whose work with the structure of coal began from the geologic side recognize that the structure is almost entirely that of altered plant tissues, although they are inclined to regard the structural constituents of coal as analogous with the minerals that make up other sedimentary rocks. The paleobotanist, on the other hand, recognizes the importance of geologic processes in the formation of coal but is inclined to interpret most of the features of coal in terms of the original plants and paleoecological conditions in the original site of deposition.

In the study of Tertiary lignitic coal, certain factors make the paleobotanical approach more important than is true for older coals. Tertiary lignitic coal retains even some chemical features of the original plant materials, for example, holocellulose (3), and these chemical features are most readily and adequately described in terms of the original plant material. The Tertiary floras of the world were composed of genera and families of plants, many of which are extant; hence, similar floras living today can be studied. The structure of Tertiary lignites is more amenable to paleobotanical study than the structure of older coals and can be interpreted more profitably in terms of botanical nature and origin of the materials. With the older coals the structurally different parts retain less of their original physical and chemical differences; also the original contributing floras are remotely related to modern floras (this is especially true of pre-Cretaceous coals).

Applications of Lignite Microscopy

Most of the work on the microstructure of lignitic coals in the past has been done in Germany, where the commercial development of lowest rank coal has been much greater than elsewhere. Stach (40), in a review of the microscopy of lignitic coal, shows the contributions the work has made to:

1. Knowledge of the origin of the coal.

2. Stratigraphic identification and correlation of beds. This stratigraphic work is important in determining and evaluating minable reserves. It is also important because knowledge of the nature of a coal can be deduced from previous work - if the bed can be identified. Study of the plant microfossils in coal, especially the pollen and spores, has been useful for identifying coal beds, both lignitic and higher rank.

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3. Utilization of brown coal.

a. Certain structural constituents of brown coal (for example, resin and wax) have special applications in technology. The distribution and concentration of such materials can best be determined by coal microscopy.

b. Manufacture of briquets from brown coal depends on structural features of the raw coal. Microscopy of coal and of the briquets has provided information of value in briquet manufacture.

Some applied research in lignite microscopy has been carried out in this country, almost all of it by the Federal Bureau of Mines. Storch, Hirst, Fisher, and Sprunk (43), and Fisher, Sprunk, Eisner, O'Donnell, Clarke, and Storch (24) report work on hydrogenation of coal, including lignite, in which the effect of petrographic composition on yields on hydrogenation was studied. Fort Union lignite was found to give satisfactory yields on hydrogenation. This was thought to be related to the predominance of petrographic constituents that are translucent in thin sections. Some other American lignites give higher yields than Fort Union lignite, probably because they contain a larger proportion of waxy and resinous material (34).

Selvig, Ode, Parks, and O'Donnell (37) report a study of extractable waxes in American lignites. The Fort Union lignites tested gave relatively low yields on extraction. The yields of wax apparently were related to petrographic composition. Petrographic analysis of a wider range of Fort Union lignites probably will help to indicate which beds (or parts of beds) are most promising for applications of this sort. There is considerable variation in petrographic composition of Fort Union lignite, and local occurrences of wax-rich lignite in the region are possible.

Selvig (34) gives data for the yields of tar obtained from various American lignites of different petrographic types by low-temperature carbonization (500° C.). Here, also, yields appear to correlate well with petrographic composition. It may be possible to predict from petrographic analysis the Fort Union lignite beds, or perhaps the parts of beds, that will give highest yields of tar. The advantage of petrographic investigation for this purpose is that it can detect variation between parts of one bed that would not otherwise be noticed. For example, 2 lignite beds could give identical overall carbonization (or wax-extraction) yields, yet 1 of the beds might have a portion of tar-rich (or wax-rich) coal that is diluted in the overall test. Petrographic analysis could be expected to reveal this concentration of tar-rich (or wax-rich) coal, and it might be possible to mine it selectively.

To summarize: Petrographic and paleobotanic studies should be of value in the future development of Fort Union lignite, as a stratigraphic tool, as an aid in selecting beds for special purposes, and as a basic research method in investigating the nature of this coal and its characteristics in various processing applications.

Techniques for Paleobotanic Study

As previously pointed out, Tertiary plants were so closely related to modern plants that quite precise paleobotanic studies are possible. Identifications, at least to broad groups of extant plants, is usually possible; as a result, accurate knowledge of the floras that provided the plant material for Tertiary lignites is acquired. This makes possible generalizations about conditions in the basin of deposition, which may help to answer questions about the nature of the coal. For example, Thomson and Pflug (46) were able to correlate petrographically different bands in certain German brown coals with fluctuating depth of water in the place of deposition by studying the fluctuating content of certain plant microfossils. Many other examples of this sort of unified paleobotanic-petrographic technique are to be found in the literature on investigation of German brown coal.

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Woods, seeds, and fruits, even flowers, occur in deposits of lignitic coal and can be separated out and studied by conventional botanical techniques. The preservation of structural detail is often startling. Various chemical reagents, such as strong alkalies and oxidizing acids, can be used to separate pollen, spores, and leaf cuticles, which are waxy, from the matrix of lignitic coal as a whole. This is called maceration. The microfossils separated are often in an excellent state of preservation and have very characteristic structure, hence are amenable to botanic study. Extensive use is made of modern material for comparison purposes in such investigation. Figure 15 shows photomicrographs of pollen grains separated from an American lignitic coal, compared with pollen of the closest extant relatives (48).

Many paleobotanic studies have been made of German brown coal but very few of American lignites. The contributions of Barghoorn and Spackman (3) on the megafossils, and of Traverse and Barghoorn (49) on the microfossils, of the Brandon, Vt., lignite, and of Miner (29) and Wilson and Webster (52) on microfossils of Fort Union coal from Montana represent the only modern published paleobotanic studies of American deposits of Tertiary coal, although incidental use of fossils from lignite has been made by others.

Techniques for Petrographic Investigation

The microstructure of coal may be studied by several techniques. Very thin films (in the range of 5 to 10 microns thick) can be prepared that can be studied under the microscope by transmitted light, or very smooth polished surfaces can be prepared that are then studied by reflected light under the microscope. Or, the coal may be partly decomposed (macerated) with various acids and other chemicals. This can be used to isolate certain fractions of the coal for microscopic examination; although occasionally used for petrographic research, this is primarily a paleobotanic technique (see previous discussion).

Thin films (sections) of lignite can be prepared by using the biological microtome, but most sections for petrographic study are made by the techniques developed for making sections of rock. A surface of a small block of coal is polished smooth and glued to a microscope slide with a special transparent thermoplastic glue. The coal is ground away on lapidary wheels and on hones and glass plates until a thin film remains. This is polished smooth at a thickness of about 10 microns. The film of coal is protected with a coat of some transparent mounting medium and a thin glass cover. Care must be exercised at all stages of the operation to prevent exposure of the lignite because of its instability in the air. The section thus prepared can be studied with a biological microscope by transmitted light. Some constituents may remain opaque even at thicknesses of the order of 10 microns and cannot be satisfactorily studied by this technique. These constituents make up a relatively small fraction of the total in Fort Union lignite. Thiessen, Sprunk, and O'Donnell (45) have described the general techniques used in making the sections. Traverse (47) has described the technique as applied to Fort Union lignite and a modification of it for use with crushed lignite. The crushed lignite is embedded in plaster of Paris with a resin binder then sectioned by the same techniques used for blocks of lignite. Figure 9 is a photomicrograph of part of such a preparation of crushed lignite.

Most European work on the petrography of lignitic coal has been done with the polished-surface technique and reflected light. A surface of a small block of coal is polished to a very smooth finish. This block is mounted, and the surface is studied by reflected light with special microscopic equipment. As pointed out above, material opaque in thin section cannot be studied by transmitted light, therefore this technique is preferable where there is considerable opaque material. This is especially true of the higher rank coals, since there is a general increase in

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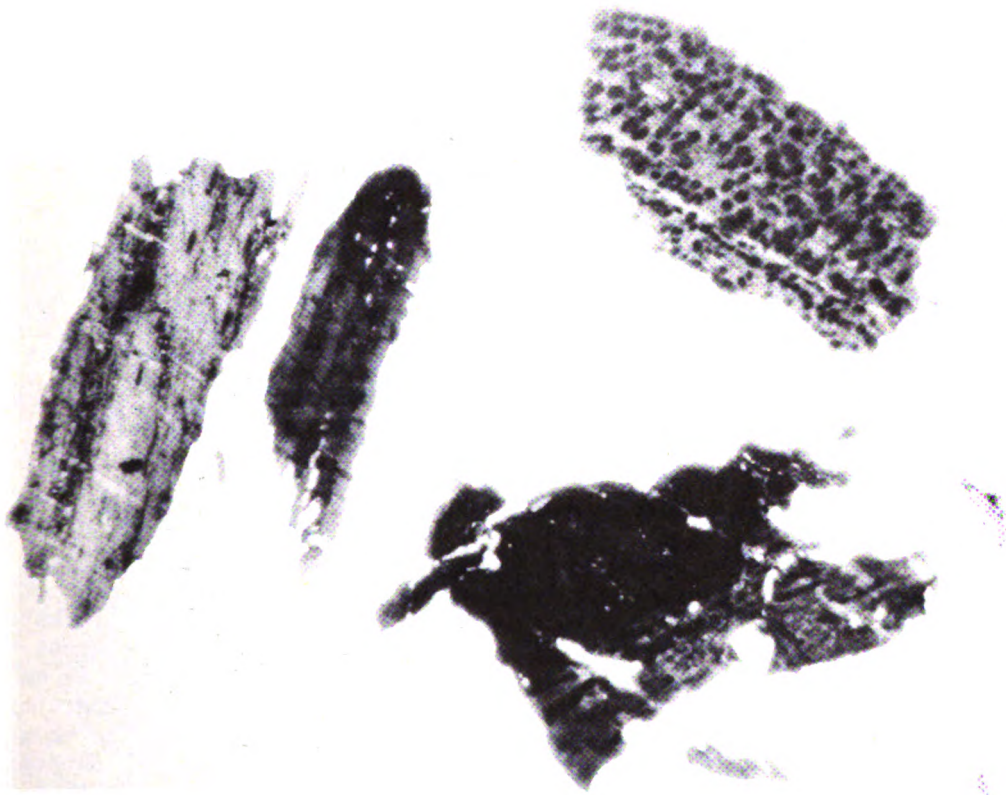

Figure 9. - Photomicrograph of a thin section of crushed particles of lignite.

From Dakota Collieries mine, Zap, Mercer County, N. Dak. The particles were embedded in a block of plaster of Paris before the section was made. Photomicrograph made by transmitted light. Magnification: 58x. Natural color under the microscope: mostly yellowish brown to reddish brown or reddish, some black in lower right fragments.

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opacity with increase in rank. For lignitic coals, embedding in wax or other solid embedding medium and careful protection of the polished surface are necessary in preparing blocks for study by reflected light, because the rapid loss of moisture and consequent deterioration of these coals in air.

Teichmüller (44) has pointed out that, since transmitted-light studies are best for the translucent fraction of sections and reflected-light studies for opaque material, a combination of the techniques would be desirable. Teichmüller has demonstrated in a very well illustrated paper that a specially prepared thin section can be studied by either or both methods. Such a section is called a polished thin section. To date, however, nearly all work has been done by one technique or the other. European investigators have mostly used reflected light; American investigators, transmitted light.

Terminology of Coal Petrography. - Differences in technique have played an important part in development of the terminology of coal petrography. In Europe, coal petrography began with examination of coal by the naked eye and continued with the microscopic examination of polished surfaces. The terminology used for gross features of polished surfaces was carried over into microscopic study, with the result that there has inevitably been confusion about definitions. The European nomenclature has emphasized the analogy between the structural constituents of coal and the minerals that make up rocks, and precise definitions of a rather large number of such constituents have been attempted. This classification and nomenclature, however, are applied to bituminous coal only. Even German petrographers of brown coal use no well-established standard system of classification and terminology. The emphasis is strongly paleobotanic, and the names used for structural units differ with the investigator.

Some American coal petrographers have followed the European pattern, but most American work has been done using the techniques and nomenclature of Thiessen and his coworkers and successors in the Federal Bureau of Mines. The nomenclature of the Thiessen system is based only on microscopic study of thin sections. It is a simple classification and has been applied to lignitic as well as to higher rank coals. There is no doubt that refinements of the nomenclature are necessary. Perhaps in lignitic coals new nomenclature is especially desirable because of the great variety of chemically different components. However, the Thiessen nomenclature is an acceptable framework on which to build a meaningful nomenclature for the petrography of lignitic coal, although it must be realized that the significance of the broad categories is not the same for lignitic as for bituminous coals. That is, anthraxylon in lignite must not be assumed to be the same chemically as anthraxylon in bituminous coal. Because lignite components often retain chemical features of the original plants, anthraxylon is not necessarily chemically homogeneous, even in lignite, although the evidence is that examples of the same petrographic component from different deposits of a given region are similar chemically.

The petrographic constituents, according to Thiessen's system, are:

1. Anthraxylon. Particles translucent in thin section, with cellular structure and a vertical extent in the lignite bed of more than 14 microns. In Fort Union lignite most of this is wood, but bark, seeds, fruits, and other tissues also are included. (See figs. 10 and 11).

2. Translucent attritus. Particles translucent in thin section and either amorphous or with cellular detail but less than 14 microns in vertical extent in the bed. Pollen, spores, and leaf cuticles are also included here. This might be called the fine attrital matrix of coal. (See fig. 12.)

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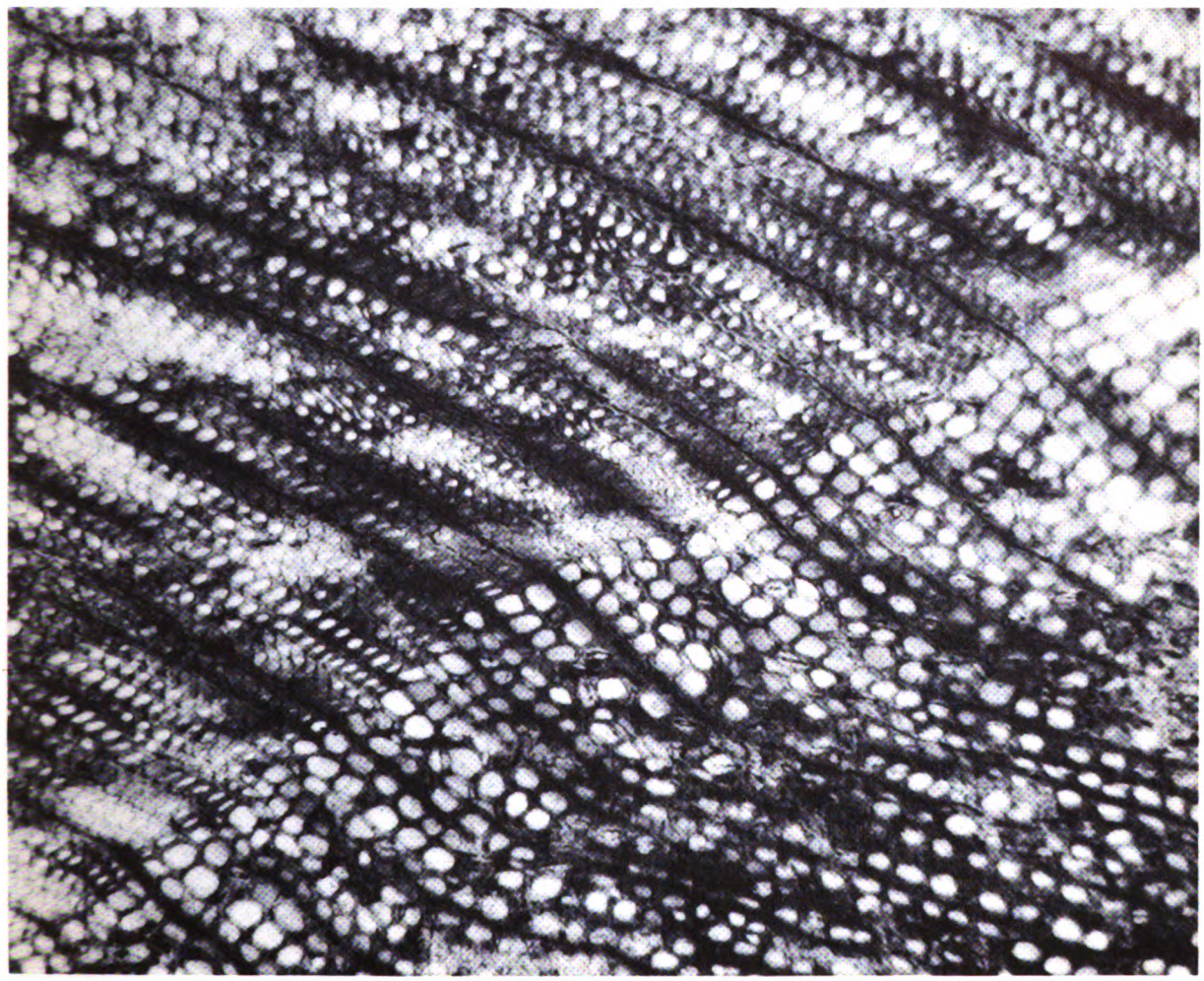

Figure 10. - Photomicrograph of a transverse section of anthraxylon (coniferous wood).

This is a portion of a thin section of lignite from a column sample collected in Dakota Collieries mine, Zap, Mercer County, N. Dak. The rows of wood elements (tracheids) are evident as perforations. The wood rays (lines between the rows of tracheid perforations) are also visible. The smaller elements in the upper left represent the end of one season of growth. The larger elements in the lower right represent the beginning of the next growth season. Photomicrograph made by transmitted light. Magnification: approximately 200x. Natural color under the microscope: Reddish orange.

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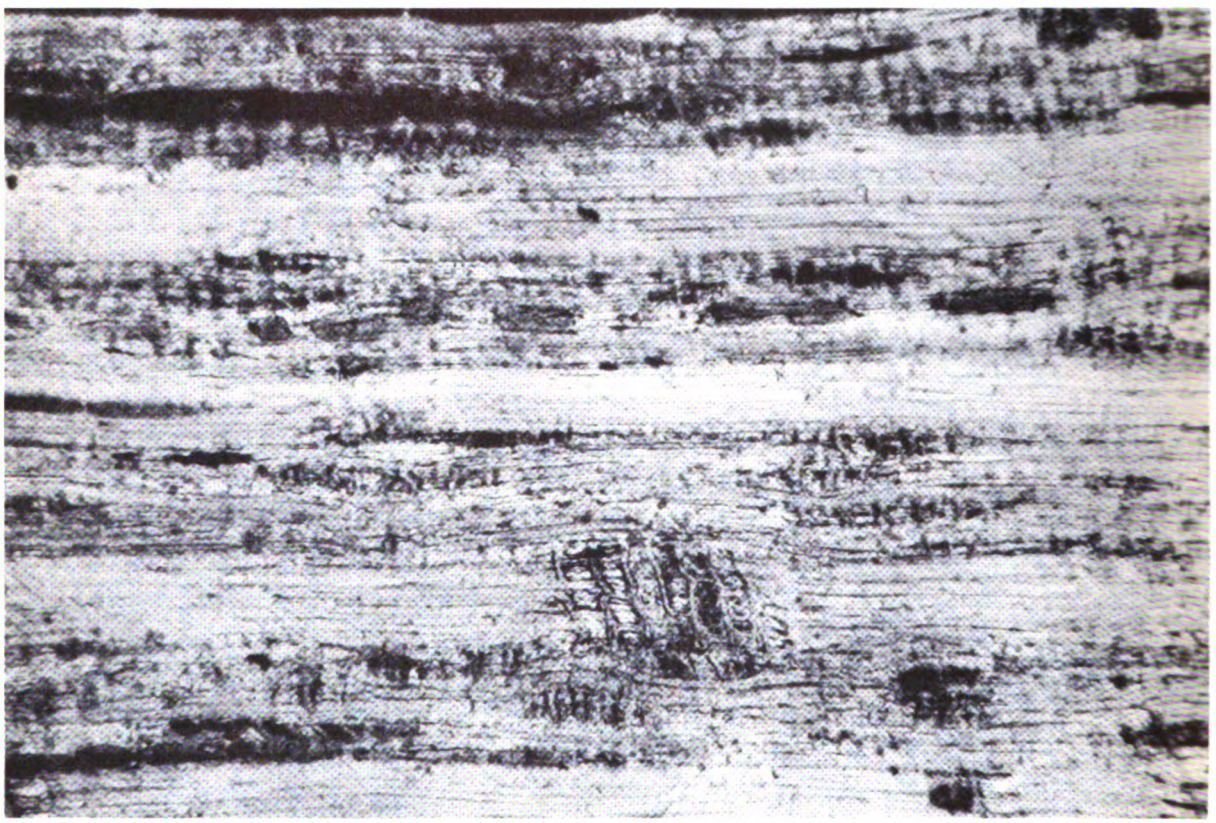

Figure 11. - Photomicrograph of a longitudinal section of anthraxylon (coniferous wood).

This is a portion of a thin section of lignite from a column sample collected in the Dakota Collieries mine, Zap, Mercer County, N. Dak. The principal elements of the wood run horizontally in this photograph, as in the coal bed. In the stem of a living tree they would be vertical. In addition to the principal elements (tracheids), rays and probable resiniferous cells are also visible. Photomicrograph made by transmitted light. Magnification: Approximately 200x. Natural color under the microscope: Orange to red.

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Figure 12. - Photomicrograph of attrital lignite.

This is a portion of a thin section of lignite from a column sample collected in the Dakota Collieries mine, Zap, Mercer County, N. Dak. The lignite illustrated is composed almost entirely of translucent attritus: A mass of small particles of macerated plant tissues (grayish), with some leaf cuticles (small whitish horizontally elongated bodies next to larger, gray elongated bands) and pollen and/or spores (small, whitish bodies scattered throughout the section). There is some opaque attritus in the section; black bodies. Most of the horizontally elongated bands are anthraxylon: leaves and small pieces of wood, for example. Photomicrograph made by transmitted light. Magnification: 90x. Natural color under the microscope: Yellow, brown, orange, red, and black.

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3. Opaque attritus. Particles that are opaque in standard thin sections (that is, sections of about 10 microns thickness) and are either amorphous or have cellular structure but are less than 37 microns in vertical extent in the bed.

4. Fusain. Same as mineral charcoal. A soft, fibrous carbonized material showing cellular structure, usually of wood, in thin section; walls of cells are opaque in standard thin sections. Particles have vertical extent in the seam greater than 37 microns.

5. Translucent mineral matter. Mineral matter that transmits light in thin section. Quartz, clay minerals, gypsum, and calcite are the principal ones in Fort Union lignite.

6. Opaque mineral matter. In Fort Union lignite, this is pyrite, or iron pyrites, an iron sulfide mineral. (See fig. 13.)

Petrographic Analysis of Fort Union Lignite

Table 10 lists the petrographic analyses of Fort Union lignite that have been published to date, with a few analyses of other American lignites for comparison. The relatively high percentage of anthraxylon in the North Dakota lignites and the predominance of the attrital constituents in the California, Arkansas, and Texas lignites are the most striking feature of this table. Much of the attrital lignite is composed of waxy material, mostly pollen, spores, and leaf cuticles. (See fig. 12.) As has been explained by Parks (30) and by Selvig, Ode, Parks, and O'Donnell (37), this relative abundance of waxy matter in the attrital American lignites accounts for the higher yield of waxes and resins obtained from them on extraction with solvents. The Fort Union lignite, which is high in percentage of anthraxylon (most of it is wood in Fort Union lignite), gives lower extraction yields. Selvig (34) has pointed out that the American attrital lignites are higher in volatile matter and higher in yields of tar on low-temperature carbonization at 500° C.

David White (50) described in detail how the highly woody (xyloid) nature of Fort Union lignite seems to be evidence of relatively rapid accumulation of the plant material, with relatively little decay or attrition. Figure 14 is a photograph of a part of a log about 18 inches across, cut across the grain with an axe for this photograph. The somewhat contorted annual rings can be seen on several cut surfaces of this log. Logs of this sort, which may be many feet long, are common in North Dakota. The wood, when freshly uncovered, retained some of the resilience of ordinary wood.

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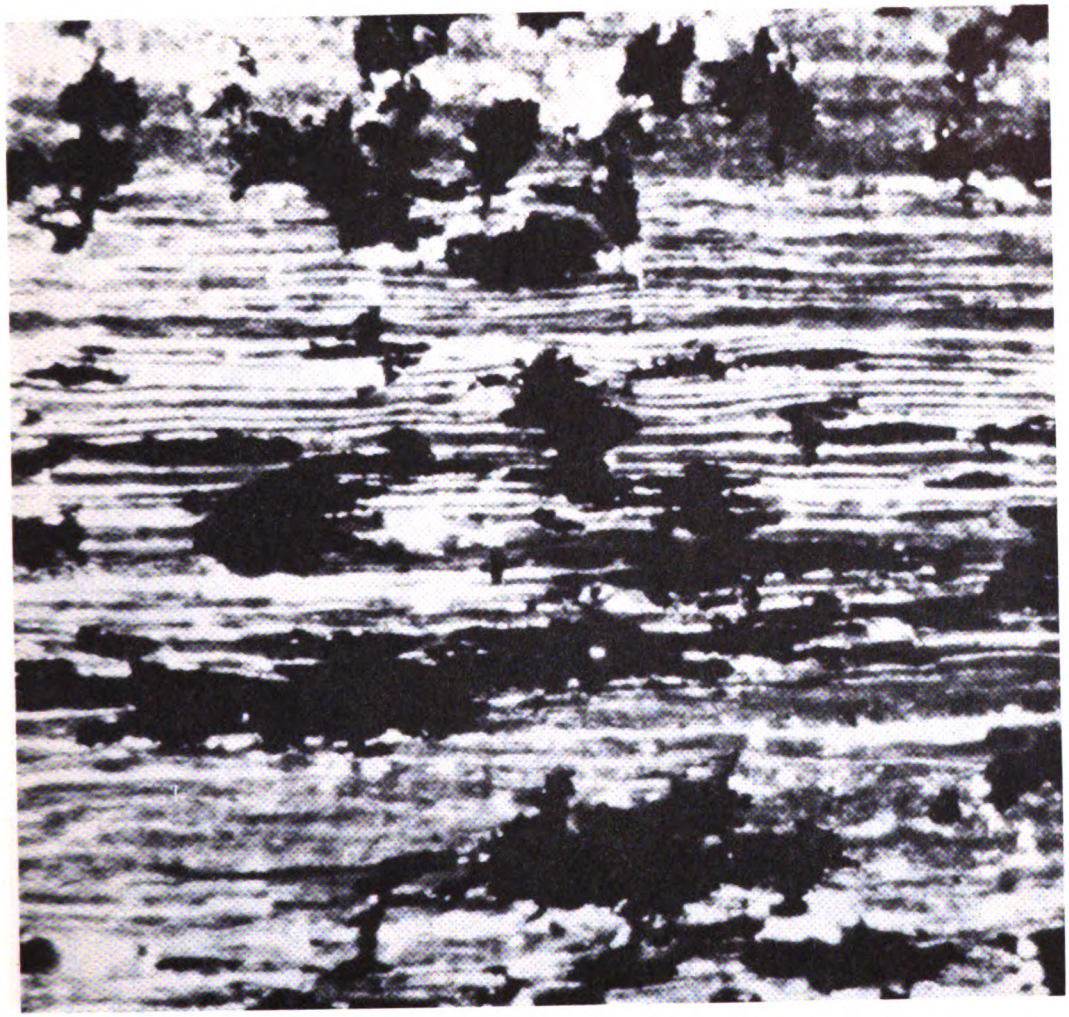

Figure 13. - Photomicrograph of iron pyrite in anthraxylon.

This is a portion of a thin section of lignite from a column sample collected in the Dakota Collieries mine, Zap, Mercer County, N. Dak. The dense black patches are pieces of iron pyrite in section. The pyrite is embedded in anthraxylon (mostly wood here)—compare with figure 9. The wood elements are oriented horizontally, as in the coal bed, although the orientation in the stem of a living tree is vertical. By reflected light, the pyrite (which is opaque, hence black, by transmitted light) has a metallic luster. Photomicrograph made by transmitted light. Magnification: 90x. Natural color under the microscope: Reddish orange and black.

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TABLE 10.—Petrographic analyses of North Dakota lignite according to the Thiessen system, with analyses of several other American lignites for comparison

Item No.	Origin of sample	Bed	Kind of sample	Percent of bed analyzed	Percent of petrographic constituents				Reference
					Anthraxylon	Translucent attritus	Opaque attritus	Fusain	
1.	American Dyewood Co., abandoned mine near Manning, Dallas County, Ark.	-	58-inch column sample.	95.1	14.8	83.8	1.4	0.0	(37, p. 41)
2.	American Lignite Products Co. mine, Amador County, Calif.	-	Top 81 inches of 157-inch bed.	86.9	10.3	89.1	.6	.0	Do.
3.	Darco No. 3 mine, Harrison County, Tex.	-	Layer sample: 30 inches of lignite from the top bed 90 inches thick.	10.0	29.7	64.4	4.9	1.0	Do.
4.	Rupp Coal Co. mine, Adams County, N. Dak.	Haynes (?)	Selected blocks of coal from face.	-	61.0	32.0	6.0	1.0	(24, p. 72)
5.	Wilton mine, Burleigh County, N. Dak.	Wilton (?)	Selected blocks of coal from face.	-	60.0	32.0	7.0	1.0	Do.
6.	"Burleigh mine", Burleigh County, N. Dak. (same mine as above)	Wilton (?)	115-inch column sample.	94.1	63.0	31.0	5.0	1.0	(37, p. 41)
7.	Baukol-Noonan mine, Divide County, N. Dak.	Noonan	Selected blocks of coal from face.	-	45.0	45.0	9.0	1.0	(24, p. 72)
8.	Do.	do.	72.5-inch column sample.	87.4	56.2	33.4	3.8	6.6	(37, p. 41)
9.	Stevens Brothers mine, Garrison, McLean County, N. Dak. Dakota	Garrison Creek (?)	Selected blocks of coal from face.	-	51.0	38.0	9.0	2.0	(24, p. 72)
10.	Beulah mine, Mercer County, N. Dak.	Beulah-Zap	Selected blocks of coal from face.	-	64.0	20.0	14.0	2.0	Do.
11.	Do.	do.	Layer sample from 132-inch column.	32.0	53.4	25.1	15.4	6.1	(37, p. 41)
12.	Dakota Collieries mine, Zap, Mercer County, N. Dak.	do.	143.75-inch column.	92.2	54.3	31.4	12.1	2.1	(47)
13.	Truax-Traer mine, Velva Ward County, N. Dak.	Coteau	120.8-inch column sample.	82.2	61.0	27.0	9.0	3.0	(37 p. 41)

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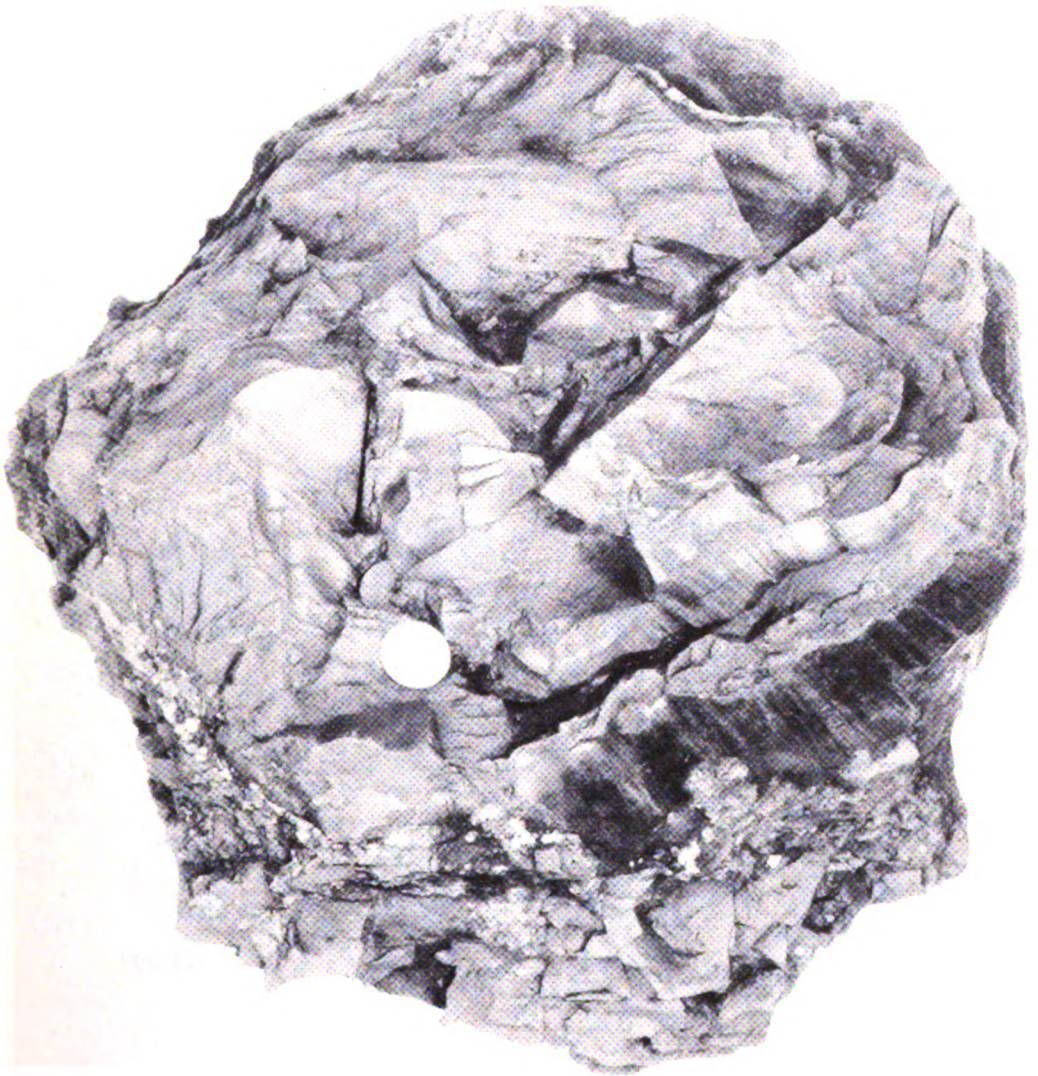

Figure 14. - Photomicrograph of part of a lignite log.

This log was about 15 inches in diameter. It was collected in 1952 from the Haynes lignite bed, Davenport mine, New Leipzig, Grant County, N. Dak. The photograph shows a transverse surface of the log, prepared with an axe. The somewhat distorted annual rings can be seen on several of the surfaces shown. The wood was of a somewhat lighter brown color than the average color of North Dakota lignite, and was resilient and woodlike in texture when fresh. The white disk on the surface of the wood is a 25 cent piece (about 1 inch in diameter), for scale.

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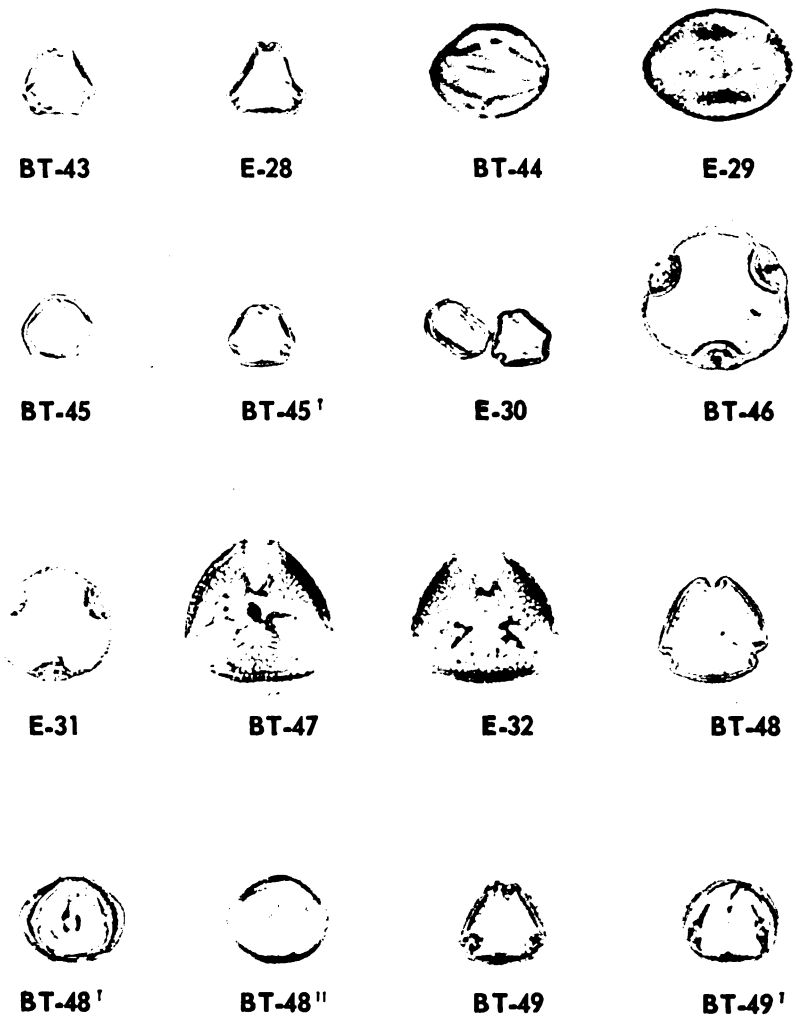

Figure 15. - Photomicrographs of pollen grains from a tertiary lignite coal. (The Brandon lignite, Forestdale, Brandon, Vt.)

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Figure 15.

The pollen was isolated from the lignite by maceration of the coal. Pollen of closely related extant forms of some are shown for comparison. Uniform magnification: 410x. This is a reproduction of a plate from Traverse (48).

BT-43	Pollen of the family Rhamnaceae (buckthorn family), from the Brandon Lignite.
E-28	Pollen of the extant buckthorn species Rhamnus caroliniana Walt.
BT-44	Pollen of the Parthenocissus-Cissus group of Vitaceae (grape family), from the Brandon lignite.
E-29	Pollen of the extant grape family species Parthenocissus quinquefolia (L.) Planch. f. hirsuta (Donn.) Fern.
BT-45 and 45'	Two views of pollen of the genus Vitis (grape) from the Brandon lignite.
E-30	Similar views of pollen of the extant grape species (Vitis tiliaefolia Humb. & Bonpl.
BT-46	Pollen of the genus Tilia (basswood tree) from the Brandon lignite.
E-31	Pollen of the extant basswood species Tilia americana L.
BT-47	Pollen of the genus Gordonia (loblolly bay tree) from the Brandon lignite.
E-32	Pollen of the extant loblolly bay species Gordonia lasianthus L.
BT-48, 48', 48", 49, and 49'	Pollen of the genus Nyssa (same genus as tupelo tree) from the Brandon lignite.

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The more attrital lignites have been derived from peats composed of considerably decomposed plant matter, hence attritus. In some attrital lignite pollen, spores, and leaf cuticles are especially concentrated. (See figs. 12 and 15 for examples of leaf cuticles and pollen in lignite.) This could be due to enrichment by decay of less resistant, nonwaxy fractions, as suggested by White. But, as many subsequent writers have suggested, an initially great concentration of the waxy plant fragments could also be responsible. Such conditions might exist in a shallow basin some distance from the shore. White noted that these nonbanded lignites with a high percentage of waxy plant fragments are obviously homologous in a lower-rank coal with cannel (bituminous) coal. White used the terms "canneloid" to describe such lignite and "xyloid" to describe typical Fort Union lignite. Selvig (34) gives the following classification for American lignites:

Type	Subtype	Appearance	Examples from table 10
Xyloid	-	Coarse to finely banded	4, 5, 6, 8, 9, 10, 11, 12, 13
Attrital	Humic	Finely banded	3(?), 7
	Canneloid	Nonbanded	1, 2

The xyloid type has a relatively smooth texture, often showing gross woody structure. In thin section the abundance of anthraxylon is apparent. The attrital type is grainy in gross appearance. In thin section the attrital type is seen to be made of finely divided plant remains, predominantly pollen, spores, leaf cuticles and other waxy material in the canneloid subtype; predominantly finely divided humic matter (more or less decomposed plant tissue of various origin) in the humic subtype.

Although Selvig does not give exact definitions of these types and subtypes, as to percentage of constituent, it appears that 50 percent anthraxylon is the dividing line between xyloid and attrital. Selvig[7] states that a North Dakota lignite (column sample from Baukol-Noonan mine, Divide County) classified as attrital type - humic subtype, in his paper quoted above (34) had the following petrographic analysis, in part: 46 percent anthraxylon, 45 percent translucent attritus. The term "attrital lignite" has usually been used primarily for the variety that Selvig classifies as canneloid attrital. It is this type that gives high yields of waxy and resinous material on extraction and high yields of tars on carbonization. Although all American lignites give relatively high yields on hydrogenation, the canneloid attrital type gives higher yields than the xyloid type or the humic attrital type. The humic attrital subtype gives higher yields than the xyloid type (34).

Selvig's humic attrital subtype may prove to be a distinct group in the Fort Union region, but there is relatively little evidence for it as yet. The example cited by Selvig is from a mine for which another petrographic analysis shows 50 percent anthraxylon (37). In principle, a Fort Union lignite composed predominantly of the same sort of translucent attritus that makes up about 35 percent of the xyloid variety should give somewhat higher yields than does the xyloid variety on carbonization, solvent extraction, and hydrogenation.

Storch, Hirst, Fisher, and Sprunk (43) describe lignite from Truax-Traer mine, Velva, Ward County, N. Dak., in terms of "bright", "semisplint", and "splint" coal. Fortunately, this classification was not used in later work on lignite. Although the terms have been defined as to percentage of petrographic constituents, the types on which the definitions are based exist only in bituminous coal.

7/ In a letter written in 1953.

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In addition to the variation in petrographic composition found between different beds, there is ample evidence of variation within the same bed. For example, figure 16 is a graph of the petrographic composition found in an analysis of a column sample, representing 11 feet, 11-3/4 inches, of the 12-foot bed, at Dakota Collieries mine, Zap, Mercer County, N. Dak. (A column sample is essentially a solid column of coal representing the entire vertical extent of a bed, or a specified part of it. For convenience in handling, a column sample is usually collected as blocks 1 foot or so in vertical extent.) In all, 188 thin sections were made from this column of lignite. The sections as a whole were then a ribbon of lignite representing the entire vertical extent of the lignite bed, or, more precisely, 92 percent of it, because of loss of coal in preparing the sections. (The overall petrographic analysis for this column is given in table 10, item 12.) In figure 16, the percentage of petrographic components is plotted against vertical extent in the seam. Each point on the graph represents one thin section from the column. Total translucent is anthraxylon plus translucent attritus. It may be noted in figure 16 that there is a significant concentration of opaque matter in the upper 4.5 feet of the column or, conversely, there is significantly less total translucent matter (anthraxylon plus translucent attritus) in that part of the column. Since there is ample evidence that the petrographic components have chemical correlatives, this type of information could be of use in developing chemical utilization of lignite. Also, as previously discussed, the petrographic pattern can be characteristic of a coal bed and then can be used to good advantage for stratigraphic correlation and identification.

Leonardite

A soft, earthy, medium-brown variety of lignite that is partly to entirely soluble in dilute alkali occurs in several places in North Dakota and is mined commercially from the Harmon bed, in Bowman County. Typically, this material is so soft that it can be crushed easily and often feels rather smooth or greasy when rubbed between the fingers.

The substance is usually called slack where mined, because of its softness, but is often referred to as leonardite by geologists and others. It was so named for A. G. Leonard, former North Dakota State geologist (15). As originally defined, the name leonardite applied only to the alkali-soluble fraction of the raw, earthy lignite. This alkali-soluble fraction was named as if it were a mineral occurring in the slack. There is, however, no sound basis for considering the substance a distinct mineral. In more recent discussion, the term "leonardite" has frequently been applied to the whole raw slack.

Leonardite has been used to manufacture brown dyestuff, or a water-softening agent, and as an oil-well drilling mud. The brown dyestuff or stain is obtained by extraction with dilute alkali. Leonardite swells and becomes greasy or gelatinous on mixture with water, hence its use as a drilling mud.

Leonardite occurs in many places in Bowman and Slope Counties, N. Dak., almost always at shallow depths. It is mined at present from the uppermost bench of the Harmon bed in the Peerless mine of the Knife River Coal Mining Co., Gascoyne, Bowman County. This uppermost bench is about 6 feet thick, separated from 2 lower benches of ordinary lignite by 12 to 14 feet of clay. The leonardite bench in the Peerless mine is at varying depths 8 to 35 feet below the surface.

There are records of leonardite grading into the harder and more compact ordinary lignite in the Harmon bed. For this reason and because of its shallow occurrence and its gross properties, leonardite is generally believed to be naturally altered (presumably oxidized) lignite. It is often referred to as weathered lignite

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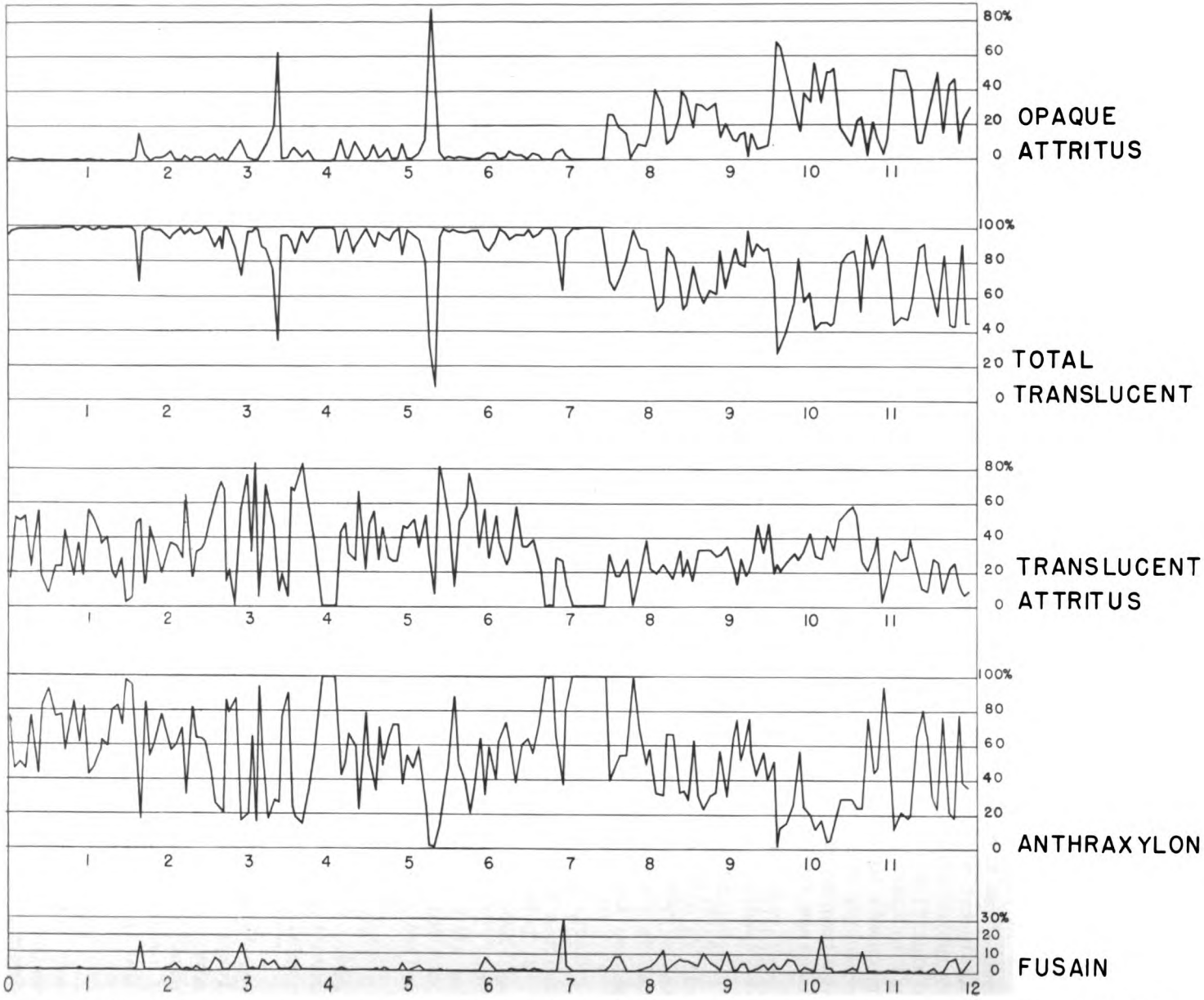

Figure 16. - Petrographic constituents of a column of lignite from Dakota Collieries mine, Zap, Mercer County, N. Dak.

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by geologists. The amenability of the material to extraction with dilute alkali supports this idea, since artificially oxidized lignite yields brown humic material on extraction with alkali much more readily than does ordinary lignite. A large fraction, sometimes 100 percent, of the nonmineral part of raw leonardite is soluble in 5 percent KOH, forming a brown solution. The brown matter can be recovered in purified form by acidification, washing, and centrifugation. There are reports of brown humic acids being leached from leonardite by ground water and redeposited on evaporation as a hard, dense material. Further study will be required to define the true identity and origin of this substance.

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4. LIGNITE MINING IN NORTH DAKOTA

The production of lignite has gradually increased since first available records and has been about 3,000,000 tons a year since 1950. The growth of the lignite industry has been a natural result of development of the consuming area and has been marked by improvements in the methods of utilization and mining, which have changed to keep pace with this growth.

The major changes that have taken place in the production of lignite are concentration of the production to a relatively small number of mines and the almost complete change from underground to strip mining. This change is shown in the following tabulation from production records (2, 8).1/

Year	Total tons produced	Production by strip mining		Production by underground mining	
		Tons	No. of mines	Tons	No. of mines
1927	1,527,939	640,709	31	887,230	122
1952	2,983,752	2,800,409	39	183,343	10

In 1927, 42 percent of the total production was by strip mining. In 1952 the proportion of total production that was strip-mined had increased to 94 percent. Over 85 percent of the production reported for underground mines in 1952 was produced by 1 underground mine (Knife River mine, Beulah, Mercer County, N. Dak.). At present, this mine is converting to stripping operations. Although the number of mines operating in North Dakota has decreased from 153 to 49 during the past 25 years, the production of lignite has doubled. Almost the entire tonnage is now produced by stripping methods.

The change to stripping methods is due in large measure to conditions that encourage surface mining but tend to discourage underground operations as the most profitable type of mining.

> Most of the rocks above and below the lignite beds are soft and unconsolidated, so much so that in underground mines it is necessary to leave two feet or more of lignite in the roof, and in some areas a comparable amount in the floor to furnish solid bearing surfaces for the timbering (1).

Large pillars are also necessary to support the roof, and recovery is low. In contrast, the poor structure of the roof and the unconsolidated structure of the overburden favor use of the stripping method. The large deposits that lie near the surface plus the advantage of a high rate of production per man-day in an era of rising costs for labor and material have all contributed to this change. Not only has the trend to stripping taken place at the larger mines but also at the smaller mines, which furnish lignite to the local markets throughout the lignite-producing region. With development of a variety of earth-moving equipment applicable to the smaller operations, including bulldozers and tractor scrapers, strip mining has also become practical for the small operators, who can contract the removal of the overburden or invest in small units of their own. The result has been the change to stripping methods by both the large and small operators.

1/ Underlined numbers in parentheses refer to citations in the bibliography at the end of this section.

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The reduction in the total number of mines has been due to the closing of numerous small underground mines serving local areas as the result of development of roads, trucking facilities, and the ability of even the small stripping mines to produce more lignite with the same manpower. Of the 49 operating mines in North Dakota during 1952, only 10 mines produced over 50,000 tons of lignite a year (8). Four of these are operated by one company, the Truax-Traer Coal Co. This firm produced almost 51 percent of the total lignite mined in North Dakota during 1952 (6).

Mining Conditions

The estimated reserves of lignite include many beds that could only be recovered by underground mining; however, only strip mines will be described, as this method has preponderant use in the industry and only those beds that are surface-minable are likely to prove economic for large-scale recovery in the immediate future.

The conditions that influence stripping methods as they are encountered in mining lignite are in many instances more favorable than the mining of other coals by this method in other sections of the country. These advantages are balanced to some extent by the severe weather conditions in winter, the comparative isolation and largely rural agriculture economy of the producing area, the absence of rail facilities in areas of large reserves, and, perhaps more important, the low heating value of lignite. Approximately 2 tons of lignite must be recovered and burned to obtain a B.t.u. value equivalent to 1 ton of bituminous coal.

Of major importance in all strip mining is the thickness of overburden in relation to the thickness of the bed. In the lignite beds being worked in 1950, the weighted average thickness of the beds worked by strip methods was 9.4 feet. Individual beds show considerable variation in thickness, ranging from 3 to 25 feet (4). The average depth of overburden in that year was 38.2 feet, a decrease from 47.5 feet in 1946. The ratio of overburden to bed thickness, based on average figures, is about half the national average of 8.0 feet (7), a distinct advantage to the lignite industry. The depth of overburden in the lignite mines of North Dakota varies from 12 feet to a maximum of 70 feet (3). At present, the maximum stripping ratio based on thickness of overburden compared to thickness of the bed, reported by any of the present mines is 10.0, which is estimated to be the economical limit.

In general, the beds are flat, with little inclination, although there may be local dips and depressions of several feet in elevation and inclinations of several degrees. The general topography of the Western Plains, under which the lignite beds lie, is gently rolling, such that variation in depth of overburden is found at most mines of about 25 feet. Overburden is composed of unconsolidated clays, with occasional shale or sandstone. It is easily removed by stripping shovels, draglines, or bulldozers, without using explosives except in infrequent instances. This is an advantage not found in other areas where drilling and blasting are required to break the overburden.

The quality of the lignite is uniform, except at outcrops where the lignite has weathered. Thickness of overburden has no noticeable influence upon quality of lignite if the bed is thick enough to permit mining. In at least one locality, good-quality lignite is found under 12 feet of overburden (3). At times a thin bed between the bed being worked and the surface occurs that is of poor quality, and this weathered and high-ash material (called slack) is usually discarded. This type of weathered and unconsolidated lignitic material sometimes is found at the top of the mined beds in a thin layer several inches thick, forming the transition layer between the overburden and the lignite.

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Outcrops of lignite beds usually are distinguished from the surrounding strata by the presence of scoria, as it is called by the miners, or clinker, as it is described by geologists. It is reddish and has the characteristics of burned clay or brick. Formed by the burning of lignite beds, which have baked and fused together the clay and minerals, the clinker is an excellent road-surfacing material and is used on public roads and at mines for surfacing haulage roads.

Percentage of Recovery

Recovery of lignite in strip mines is high. Losses are due to that which is left at the floor from which the loading shovel operates; to the loss of the berm (a wall of coal) next to the spoil piles where the spoil would otherwise contaminate the lignite; and to material removed from the top of the bed before loading. Because of ground water and the soft structure of the clays beneath the lignite, a floor sometimes must be left for the shovel. This also reduces the inclusion of underlying mineral matter in the mined lignite. When the lignite is loaded, a portion of the lignite is left as a retaining berm for the spoil pile that will be formed in uncovering the next cut of lignite. One mine has developed a vertical cutting machine (5) to make a smooth berm for retaining the spoil pile and to permit easier loading. The sheer vertical berm left by this machine is shown in figure 17, which shows the pit and the lignite bed after operation of this cutter. The cutter precedes the loading shovel and has been found to be worthwhile because it reduces contamination of the lignite and loading is facilitated.

In a recent survey (1), it has been estimated that the percentage of recovery for strip mining lignite is 60 percent based on overall reserves, including outcrop areas and losses during mining. The recovery for underground mining of lignite was estimated to be 50 percent. In the present strip mines, a higher percentage of recovery is attained, owing to the favorable location of the mines in beds of greater thickness than those included in the above estimate. Factors that have influenced the location of the present mines, other than conditions of mining, are favorable markets and rail facilities. Large reserves of lignite suitable for surface mining have not been developed because of the lack of railroad transportation. At present the investment required to furnish this outlet has prevented development of these reserves.

Ground Water

Ground water in the present lignite mines does not present great problems in the mining operations. Pumping may be required in the loading pits after heavy rainfalls, or where the ground water softens the floor of the pit so that the loading shovel cannot operate. Portable pumping units are to be found at all open-pit mines. Haulageways are usually on the top of the lignite bed in the mine and are carefully graded and surfaced through the spoil banks to the tipple. Maintenance of these haulageways is continuous to prevent stoppages due to washouts, mud, and icy conditions in winter.

Spontaneous Combustion

Spontaneous combustion of the uncovered lignite bed is not a problem in strip mining in North Dakota; however, in the case of underground mining this hazard is more important. The tendency toward spontaneous combustion of freshly exposed lignite is high. Unless adequate ventilation is provided, a sealed or closed-off room heats gradually, and eventually an active fire develops. Freshly exposed lignite is reactive to oxidation by air, and in a room that has been worked the newly exposed surfaces present a serious heating potential. Dust and loose material resulting from the mining also increase the opportunity for spontaneous ignition. At

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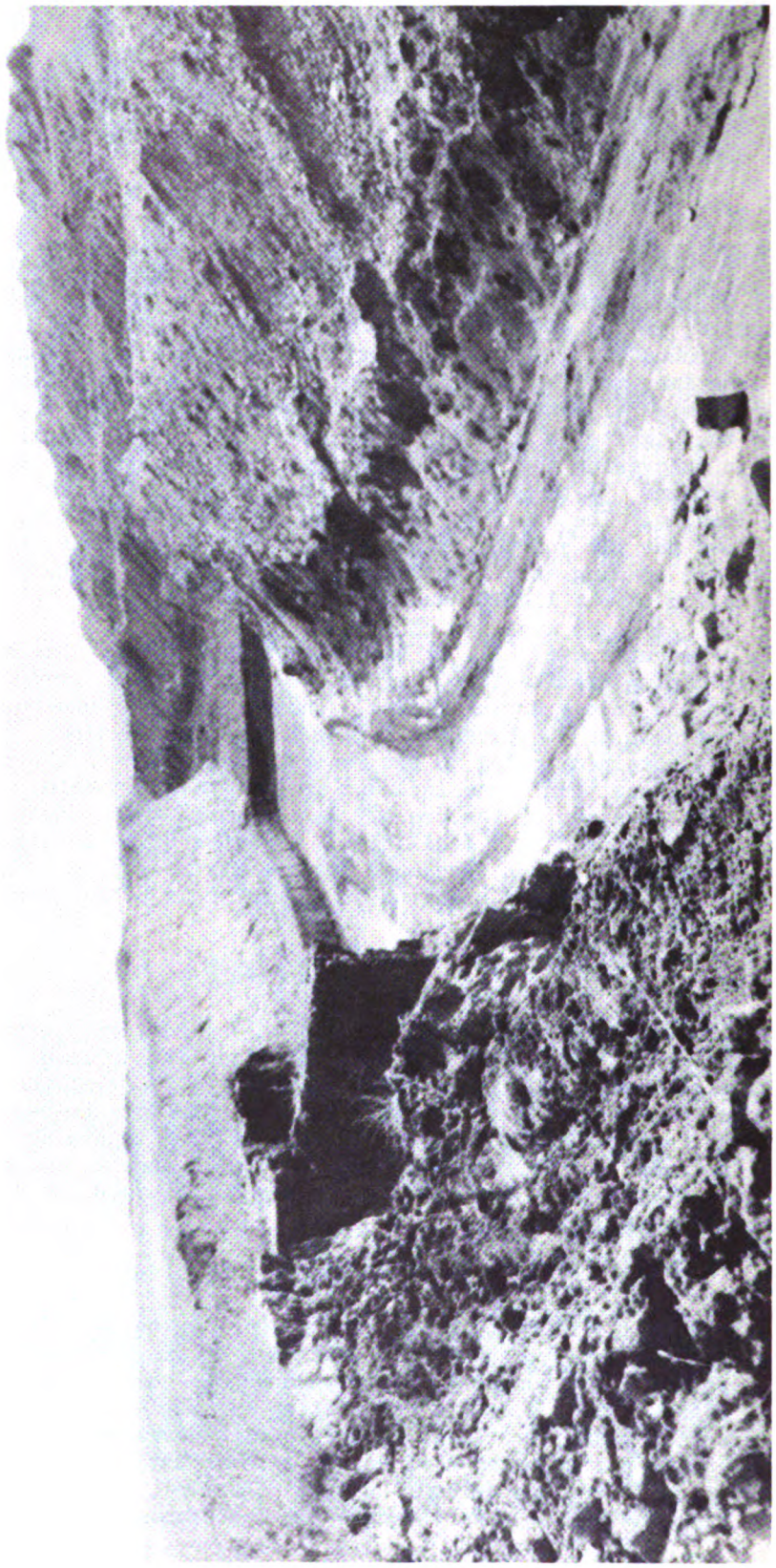

Figure 17. - Lignite seam cut vertically near high wall, Dakota Collieries mine, Zap, N. Dak.

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outcrop areas where weathered and disassociated material is found, fires start readily and are difficult to control because the fire is adequately supplied with air, heat cracks develop in the overburden, and draft is provided, permitting the fire to burn back into the bed. Several active outcrop fires have been burning continuously for years despite efforts to extinguish them. The one large underground mine still in operation has been closed at times owing to active fires. Within the last few years, this mine had a serious fire during the peak season, which resulted in suspension of operations for the balance of the season. The fire started because a severe blizzard prevented adequate inspection of the mine and maintenance of the ventilating equipment. As a result, the entire development plan had to be changed and the burning area sealed off and abandoned. In its underground operations this mine uses gunite in all main haulageways and closely supervises all suspected or known areas of heating.

In strip mining, the beds of lignite are uncovered at times a full year ahead of the loading. The adequate ventilation and the dense structure of the lignite in the bed prevent any heating. Fires have never been reported at strip mines in North Dakota.

Weather Conditions

Lignite is mined throughout the year; however, the period of highest production is during the peak demand in the winter when weather conditions are most severe. Facilities must be provided to permit operation at temperatures that are at times as low as minus 30° F. Motor-powered equipment must be sheltered when not in use because of engine-starting difficulties at low temperatures. Drifting snow must be cleared from the haulageways, lignite bed, bottoms of cars, and tipple tracks. Removing lignite from the bed does not cause difficulty, although it may be frozen, because the usual blasting charges provide adequate breakage, even at subzero temperatures. Other troubles accompanying winter operation are: Railroad cars must sometimes be moved by bulldozer because of cold-stiffened grease; lignite freezes in cars, storage bunkers, and stockpiles; heated shelters must be provided for all personnel; and worker efficiency is lowered by extreme cold. Even under these conditions, work stoppages due to the weather are rare.

Prospecting

At most lignite operations, reserves are being continuously blocked out for future operations. The usual extent of this prospecting is to establish long-term reserves for periods up to 20 years, with more detailed prospecting and drilling carried out for production several years ahead of current operations. The extent and thoroughness of the drilling vary at different mines. At the smaller mines with low production, prospecting is on a much smaller scale than at the larger mines.

Strip-Mining Methods

Stripping operations are carried out on a continuous, 24-hour-per-day basis at the large mines for approximately 10 months of the year. During the slack summer season, the stripping equipment usually is overhauled, and the major maintenance work is done. At the smaller mines, stripping usually is done during the summer season by contract or by earthmoving equipment owned by the mine. A large enough area or tonnage of lignite is uncovered to provide for winter production. At the larger mines stripping is done far enough ahead of the loading to maintain a reasonably balanced operation.

The stripping consists of removing the overburden in successive uniform cuts. This overburden is placed in the previous adjacent cut, from which the lignite has

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been removed, and forms the spoil pile. The different methods of stripping and the equipment used depend upon the equipment available and the resources of the mine owners, the depth of the overburden, and the planning of the individual supervisors. Of the mines that produce over 50,000 tons per year, 4 are operated by 1 company, Truax-Traer Coal Co. This company also conducts extensive mining operations in the coal fields of the eastern United States. Electrically powered stripping shovels are used at each of these four mines. The shovels operate on top of the lignite bed, which provides adequate support. Three of them are of 10-cubic yard capacity, and the fourth is a 17-cubic yard-capacity shovel. Two of these mines have Sauerman tower draglines, which precede the shovels in the thickest overburden. The third mine has a 6-cubic yard walking dragline (shown in fig. 18) preceding the stripping shovel, and the fourth operates only one stripping shovel (as shown in fig. 19). Other large mines operated by the Dakota Collieries Co., Baukol-Noonan Co., and Knife River Mining Co. use draglines of 7- to 10-cubic yard capacity, supplemented by smaller draglines where necessary.

The two mines using Sauerman towers in conjunction with shovels have a more complex operation than other mines. The operation of towers is illustrated in figure 20. The tower unit consists of a head tower operating from a prepared bench on the spoil pile and a tail tower, which operates on the top surface of the overburden. A scraper operated between the two towers makes a wide, shallow bench in the overburden. This operation precedes the stripping shovel. The stripping shovel then removes the remaining overburden to uncover the lignite. Usually several cuts are made by the shovel to one cut of the tower excavators. The Sauerman towers are used only where overburden is thick. Loading operations and the planning of the haulageways are more complex than in operation using a single stripping unit if interruptions are to be prevented and rehandling of overburden kept to a minimum. Operation of the towers requires rehandling some of the spoil, since they form a spoil bank of much less slope than the shovel.

Where a shovel is preceded by a smaller dragline, the dragline operates from the high wall (original ground line) and makes the first cut, particularly in making the initial cut in a new area at the outcrop line. It can pile the spoil higher and farther back than can the shovel operating from the bed. In the thicker overburden, the dragline may operate from a bench in the spoil pile, rehandling the spoil moved by the large shovel.

At mines using a dragline as the major stripping equipment, it operates from the highwall. In deep overburden two cuts may be needed, the first from the highwall and the second from the spoil bank; this is illustrated in figure 21. The dragline also may be supplemented with smaller dragline operated from the spoil bank and rehandling material, as shown in figure 22. The width of the cuts varies, depending upon the reach of the equipment. Generally an 80- to 90-foot cut is made. The angle of repose of the spoil influences the operations because a low angle of repose requires moving the spoil a relatively greater distance and rehandling the spoil pile becomes necessary at less depth of overburden. The average depth of overburden at mines in North Dakota was 38.2 feet in 1950 (7), as reported previously; however, at the older mines this figure may average 50 feet, with maximum overburden of about 70 feet. The overall average is influenced by several recently opened mines where overburden is less than the previous average.

Comparative figures of relative costs at the various operations are not available; however, it is significant to note that the larger companies, other than Truax-Traer, operate draglines for stripping rather than shovels. The lower investment cost of draglines is perhaps of major significance, although the dragline's versatility may also influence the choice. The clay overburden and the relatively level terrain favor the use of draglines. Absence of rock permits as good efficiency with

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Figure 18. - Six cubic yard walking dragline, loading shovel, and truck trailer, Dakota Star mine, Hazen, N. Dak.

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Figure 19. - Stripping shovel and loading pit, Velva mine, Velva, N. Dak.

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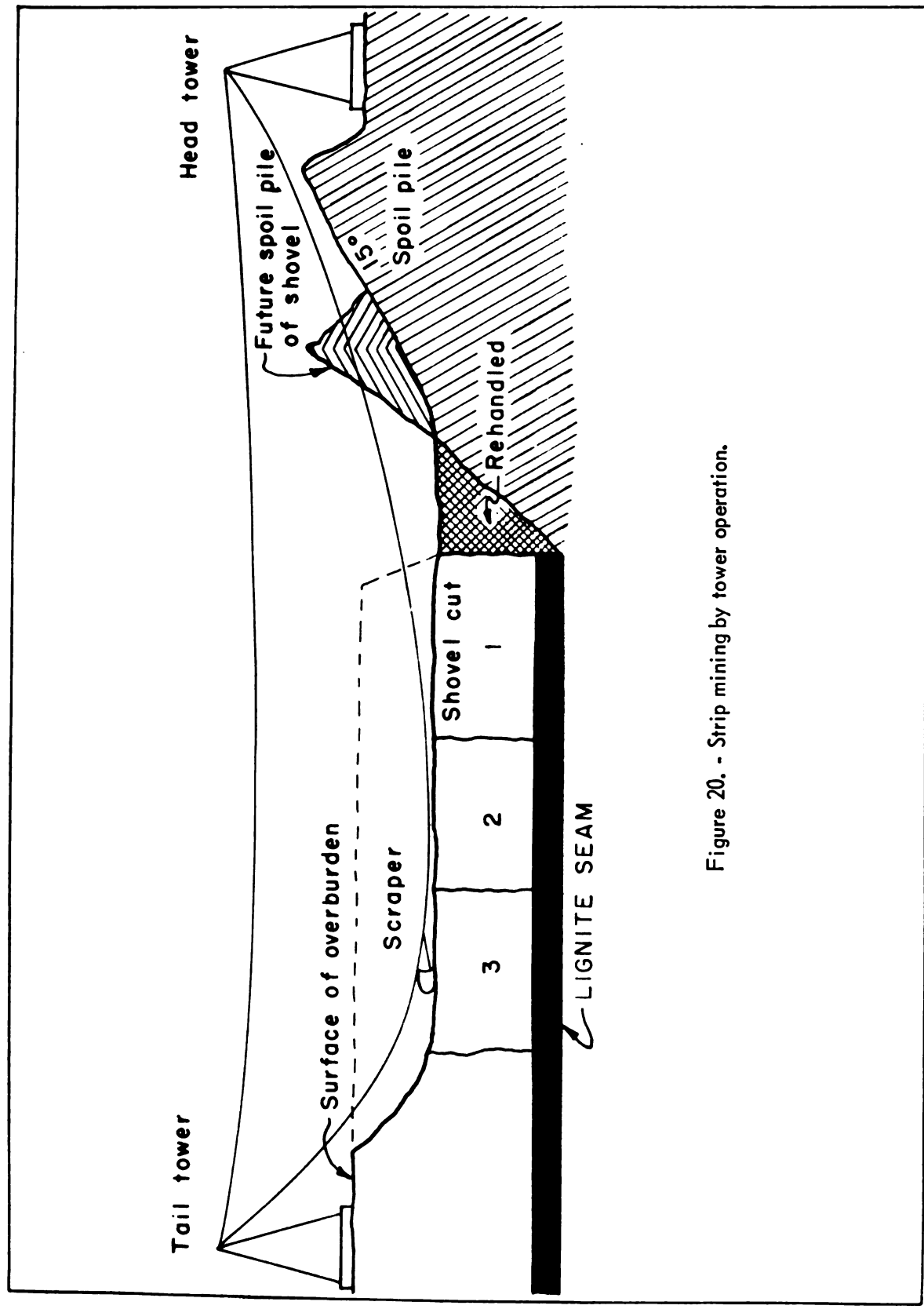

Figure 20. - Strip mining by tower operation.

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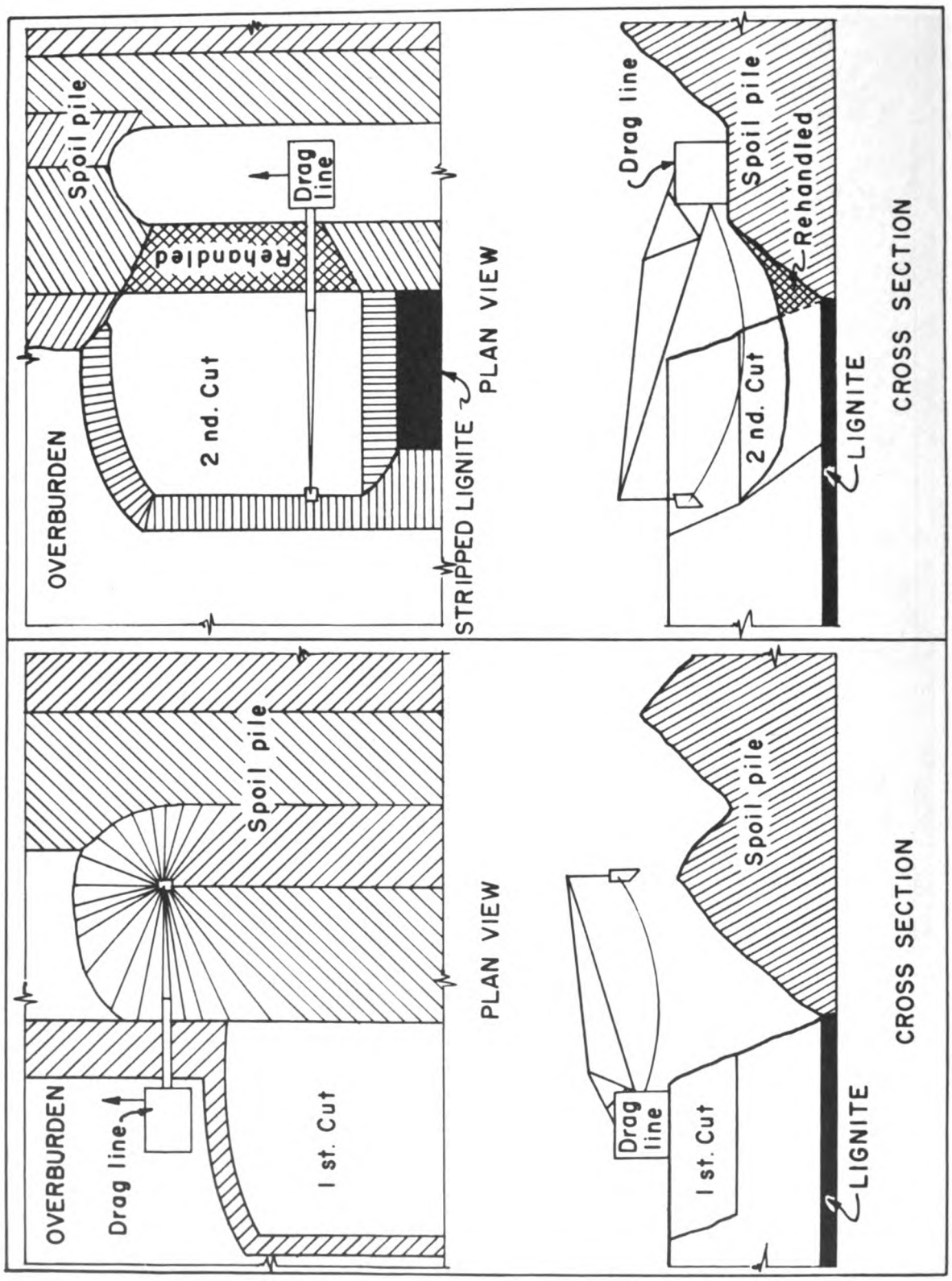

Figure 21. - Dragline operation in deep overburden.

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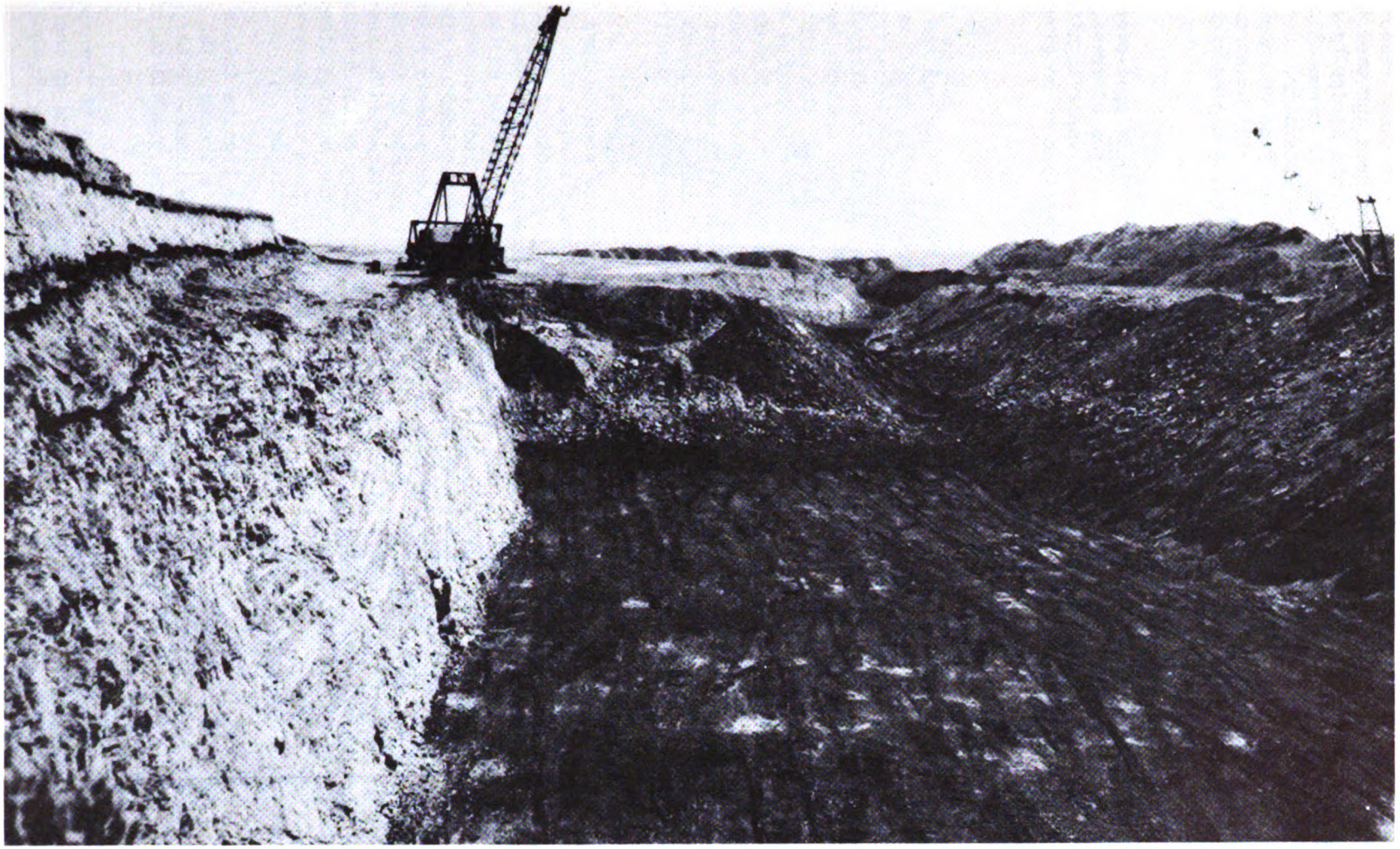

Figure 22. - Seven-cubic yard walking dragline removing overburden, 3.5-cubic yard dragline rehandling spoil; Dakota Collieries mine, Zap, N. Dak.

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draglines as is obtained with shovels working from the bed. It seems reasonable to predict that more efficient earthmoving machines will be designed and used in lignite mining, with resulting reductions in costs of mining, where stripping conditions are favorable. Flat beds, relatively flat terrain, and the unconsolidated nature of the overburden are all ideal for a continuous-type excavator. Such a machine could easily be adapted to any changing condition likely to be encountered at the lignite mines. Greater utilization of lignite probably will be accompanied by marked development in the type, size, and capacity of lignite-mining machinery.

Reclaiming the Land

Little concern has been given as yet to reclaiming of the stripped-over land. Attempts have been made to seed the spoil piles with various types of grass, with some success. Because of the low value of the surface in areas where lignite is mined, there has hitherto been little necessity for consideration to be given to this phase of strip mining.

Loading

Stripping uncovers the lignite bed well in advance of loading, and the exposure of the surface results in a layer of slacked and weathered lignite, which must be removed. This usually is done with a road grader or a bulldozer. In carrying out this operation, all extraneous mineral matter not removed during the stripping also is removed. The lignite as loaded, therefore, is uniform in ash content, and every effort is made to maintain this consistency. Before it is loaded, the lignite is loosened by small charges of dynamite placed at intervals to break the bed structure and reduce wear on the loading shovel. The amount of explosive used depends upon the degree of breakage desired. In summer the charges are increased so that maximum breakage occurs because the entire output is crushed. In winter lump sizes are desired for the domestic market, and breakage is kept at a minimum. Although the lignite can be loaded without using explosives, blasting generally is practiced at all mines.

Electric power shovels of 1- to 7-cubic yard capacity are used to load the lignite from the bed to the hauling vehicles (7). In the larger mines, with one exception, the haulageways are on top of the lignite bed, and the width of the loading pit is reduced to provide this haulageway. In the one exception, the bed is too thick to permit use of this system, and the haulage trucks are loaded on the bottom of the bed. A foot or so of the bed may be left to provide a floor for the shovel and to prevent loading the bottom lignite when of poor quality. Loading pits are comparatively dry, but pumps are provided to remove water after a heavy rainfall. In loading the lignite, no attempt is made to remove small pockets of impurity, although, in some mines, portions of the bed may have to be discarded because of the concentration of high ash material. Near outcrops, the quality of the lignite is poor and is discarded if the initial cut has been made near the outcrop line. The lignite from a given mine shows little variation in quality from year to year, owing both to the uniformity of the beds and to the care taken in mining.

At the smaller mines the diesel loading shovel dumps the lignite into a self-powered conveyor, which delivers the lignite to the consumer's trucks. The conveyor passes over a small screen, which eliminates a portion of the fines. Other small mines operate tipples to separate the fines from the lump. The production of these smaller mines goes largely to the domestic market.

Euclid trailer trucks of 20-ton capacity usually are employed to transport coal from mine to tipple. Figure 23 shows loading of one of these trucks at one of the larger mines. Figure 18, an illustration of the mining operation at another mine,

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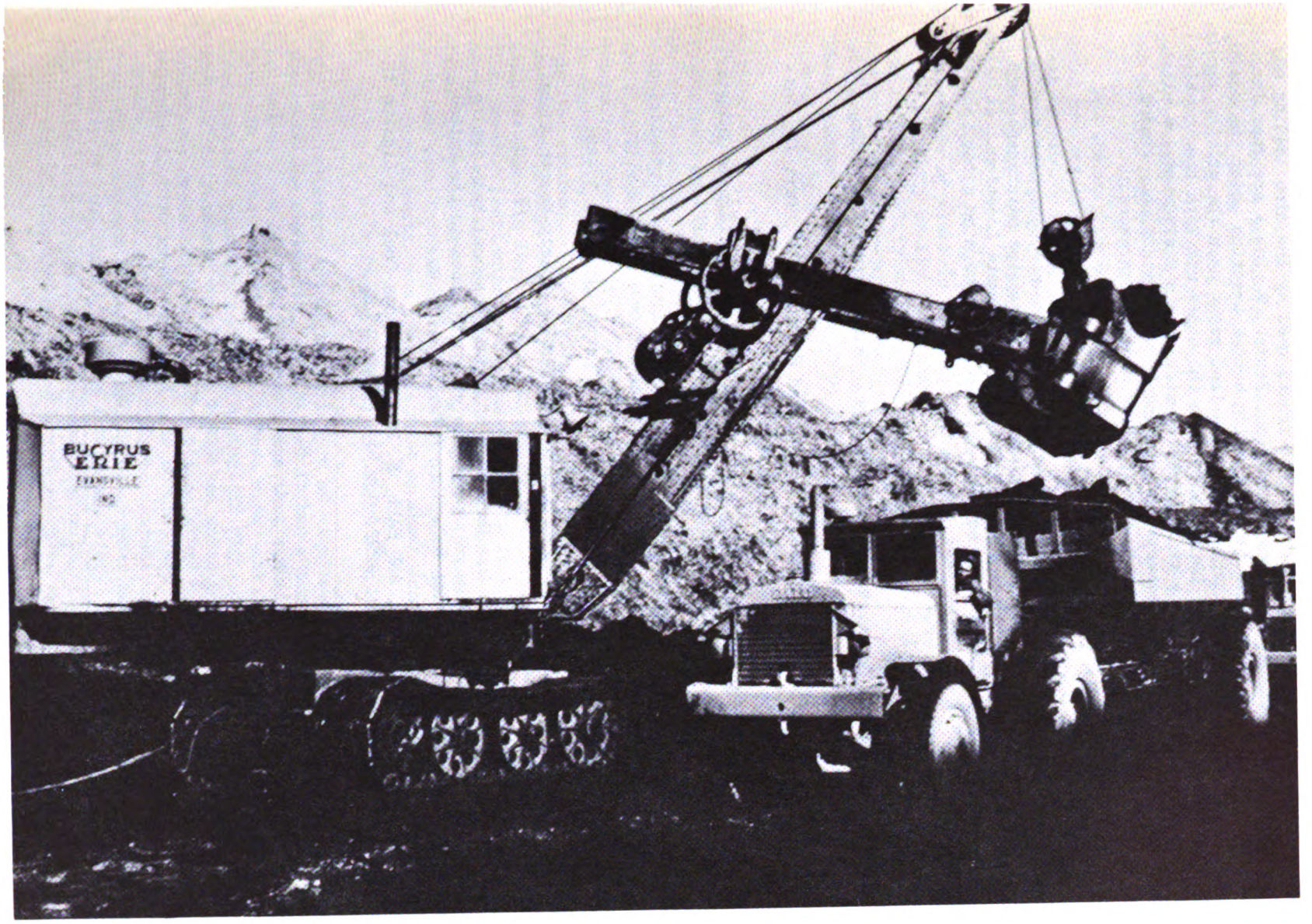

Figure 23. - Loading shovel and truck trailer.

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also shows loading of a truck on the top of the lignite bed. The number of trucks operated at each mine varies from 5 to 7 (3). Trucks used by the mine loading on the floor of the pit (Knife River Coal Mining Co., Beulah, N. Dak.) are rear dump Mack trucks. It is felt that these trucks provide better traction under the conditions found at this mine, since the weight of the load rests upon the driving wheels. The distances the lignite must be hauled vary with the mines and with the location of the loading pit at the time. A maximum of 4.3 miles and a minimum of 1/4 mile are reported (3). The main haulageways are permanent, well-maintained, graded roads. Feeder roads are built through the spoil as mining progresses.

Facilities at Mines

The large mines have considerable investment in maintenance equipment and facilities. The loading shovels and the stripping equipment require maintenance and repairs, which must be done at the mines because of their remote location. At least two of the larger mines have provided housing facilities at the mine sites, but this is not general.

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5. PREPARATION

Preparation processes in the lignite industry at present consist of crushing and screening the mined product into the various commercial sizes and, in some instances, treatment with oil to reduce dust formation and improve handling characteristics. Other processes common to the coal industry, such as reduction of mineral matter by washing, are not practiced, because the ash content is usually quite low and because lignite, as mined, is singularly unresponsive to mechanical cleaning.

The change from early use of run-of-mine to the present-day use of prepared sizes has resulted from changes in the largely rural lignite-consuming region. Electrification during the last decade has been greatly expanded, with a resultant reduction in the use of domestic lump size and an increase in industrial sizes. Home furnaces were converted to automatic stokers, creating an increased demand for stoker fuel, but liquid-fuel burners, providing more convenience, have taken over an increased share of the domestic heating market, contributing incidentally to increased use of electric power. Accompanying this trend has been closer supervision of fuel quality by the power companies. The mines have increased efforts to provide uniform quality in both ash content and size preparation. In an attempt to regain the domestic market lost to competing fuels, the handling characteristics of lignite have been improved by increased use of treating agents to reduce dust. These changes have resulted from growth and transition; other changes can be expected to follow.

Size Preparation

Major investments have been made in preparation equipment at the comparatively few large mines that supply fuel to industrial and utility companies for use in automatic combustion equipment and to rail-served retail outlets that meet local demand for domestic fuel. The market for domestic sizes is seasonal. In summer, the entire production from these larger mines is crushed because of the reduced demand for domestic fuel. Domestic lump sizes are not stored during summer because of degradation by slacking. Of the total production of lignite in 1951, 76.4 percent was crushed. Considering only those mines that have crushing equipment, 90 percent of production was crushed in the same year (3).[1/] The fraction not crushed includes domestic lump sizes produced by the larger mines and the total output of the numerous small mines, which operate only in winter to supply local demand. During the last decade several large strip mines designed primarily to supply industrial consumers have been opened, two new tipples have been erected, and new equipment has been installed and other improvements made in existing tipples. Many of these developments have resulted from consumer demand for a more uniform product.

Characteristics of Lignite in Size Preparation

The structure and characteristics of lignite in place change rapidly upon exposure to the atmosphere. In the bed it has a tough resilient structure. It can be removed from the bed in large lumps that are slablike in shape and difficult to fracture in the vertical plane. These slabs may be several feet thick and 3 or 4 feet across. Although moisture content is high, it is not present as surface moisture but is retained within the cells and pores of the lignite itself. The surface, therefore, appears dry even though the moisture content may exceed 35 percent. Upon exposure to air, rapid moisture loss occurs, and cracks and fissures appear on the surface, eventually causing the lump to degrade. This is one reason why domestic lump sizes are not stored during the hot summer months. Even in winter, if the humidity is low, dust will form in storage bins.

1/ Underlined numbers in parentheses refer to citations in the bibliography at the end of this section.

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Sizes Produced

Various sizes are produced at the different mines to meet market requirements. Designations in common use are tabulated in table 11. A standard size classification system has not been adopted by the industry.

In general, as-mined lignite passing a 2-inch or smaller screen is called screenings or industrial. To this product may be added lignite having a 2-inch or smaller top size that is produced in crushing and screening other sizes. In some cases the minus-1/2- or 3/8-inch fraction is removed from the 2-inch screenings, and the resultant double screened size is sold as industrial stoker or rescreened screenings. Because the extraneous mineral matter in the bed and other refuse introduced during mining tend to concentrate in the smaller sizes, the quality of the screenings depends in large measure on mining practices. Size distribution in the screenings varies with the loading schedule, since the fines produced in crushing the larger sizes are added to the natural product.

TABLE 11. - Common designation for lignite sizes, as produced

Designation	Size, inches
Lump	Plus-8 Plus-6
Furnace	8 by 4 6 by 3
Stove	4 by 2 3 by 2
Nut	2 by 1 2 by 1-1/2
Stoker, crushed	2 by 0
Industrial or screenings	2 by 0
Industrial stoker or rescreened screenings	2 by 1/2 or 1-1/2 by 1/2

Lump sizes above 2 inches are of more uniform quality. Stoker size prepared by crushing lump lignite is designated by the word crushed. The crushed product has a more uniform size distribution than the regular screened size. For example, a product produced by crushing 4- by 2-inch stove to minus-2-inch would be called 2- by 0-inch crushed or crushed stove. In addition, nut sizes of 2- by 1-inch or 2- by 1-1/2-inch may be screened from the crushed product. Large-size double-screened coals used in domestic heating and cooking equipment are described by their use, such as plus-8- or plus-6-inch lump, 8- by 4-inch or 6- by 3-inch furnace size, and 4- by 2-inch or 3- by 2-inch stove size. Lignite in the stoker or nut sizes often is mixed with eastern bituminous coals and used in stokers designed for the eastern coals.

Stockpiling Excess Fines

The mines usually can dispose of screenings, which contain all the fines, to various users who are willing to accept the variation in quality and size distribution for a reduction in price. No size designation for the fines is universal within the industry; however, it is generally considered to be minus-1/2-inch. The sale of this material is advantageous to the mines because stockpiling represents a net loss.

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Today most mines can dispose of fines in the screenings. In the past, there has not always been a market for these fines, and stockpiling has been necessary. Efforts to utilize the fines from the stockpiles have not been very successful, because the original ash content of the material is relatively high, and some contamination takes place during storage. As a general rule, stockpiled fines now have questionable commercial value.

Size-Reduction Equipment

Toothed double-roll crushing equipment has been found to be particularly well suited for size reduction of lignite. Impression of the teeth into the lump as it passes between the rolls, accompanied by the shredding or tearing action, is particularly effective in overcoming the tough, resilient structure of the freshly mined lignite.

At the larger mines, all of the lignite passes through a primary breaker, where the large lumps are reduced to a more convenient size. Adjustments are made in the roll spacing to meet the seasonal variation in demand for lump sizes. The presence of rock in the lignite is negligible; however, an occasional piece of hard shale is encountered. The most common size and make of primary crusher at the North Dakota mines is the 30- by 72-inch McNally-Pittsburgh double-roll breaker, which generally will handle the largest mined material (4). The size of the driving motors varies from 50 to 100 hp., depending on load requirements. During winter the crushers are adjusted to produce a top size corresponding to the size of the domestic lump, usually 8- to 12-inch.

Following the breaker, the lignite is passed over a shaker screen, where the various lump sizes are separated for sale or additional crushing. McNally-Pittsburgh Gearmatic double-roll crushers are used by the majority of the companies as secondary crushers. The teeth of this type crusher are cone shaped, and two standard lengths are available, depending upon the size of the feed. If the crusher is used to reduce 7- or 8-inch lump, it is equipped with the longer 1-3/8-inch teeth. When used to reduce the size of 4-inch lump to minus-2-inch stoker size, shorter 7/8-inch teeth are used. The usual size of secondary crushers installed in present tipples is 24- by 48-inch, although several tipples have 36- by 48-inch or 30- by 60-inch units where greater capacity is required. The 24- by 48-inch crushers have driving electric motors varying in size from 30 to 50 hp. and have capacities up to 150 tons per hour. Several crushers using the longer cone teeth for the larger size feed are driven by 100-hp. electric motors and have an estimated capacity of 300 to 350 tons an hour. There is no fixed practice in regard to motor size. The tendency apparently is to provide a large enough motor to prevent any stoppage from overloading.

In general practice, a size-reduction ratio of 2 is achieved in each double-roll crusher. The capacities of the equipment when lignite is crushed are estimated by mine operators to be approximately one half of the rated capacity for crushing bituminous coals because of the tough, fibrous character of lignite. The power required to operate the tipple is estimated by 1 company to be 40 percent of the total power consumption of the mine. Using this as a basis, tipple power requirements for 4 of the large mines vary from 1.0 to 2.5 kw.-hr. per ton. This estimated power consumption varies with the mine operations, the sizes produced, and the equipment used in the different tipples.

Other types of crushing equipment can be used in the size reduction of lignite. Forty-eight-inch Williams swing hammer mills have been used to reduce 8- by 5-inch size to stoker size. One such mill, driven by a 125-hp. motor, had an estimated capacity of 150 tons an hour. A greater size-reduction ratio is obtained with this

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type crusher than with the double-roll type, but the increased fines have imposed a marketing problem. At two tipples hammer mills have been replaced with double-roll crushers.

Handling Equipment

In the lignite industry the screening and conveying units are very similar to those used for bituminous coal and perform satisfactorily. A bulk flow-type conveyor installed for use in the gasification pilot plant, Bureau of Mines, Grand Forks, N. Dak., gave temporary difficulty in handling lignite. Particles wedged between the flights and conveyor casing and stopped the conveyor. A change in the design of the flights corrected the difficulty. The high angle of repose of lignite, particularly for the smaller sizes, retards the flow of material in chutes and hoppers. Hopper bottoms and chutes must be designed with steeply sloping bottoms of 60° or more. A slight obstruction in the hopper bottom or chute can cause stoppage. This difficulty apparently is caused by the wedge or platelike shape of the lignite particles.

Tipple Operation and Capacity

Tipples and the mines as a general rule are operated continuously throughout the winter, regardless of weather conditions. There is no apparent difficulty in handling and screening lignite at low temperatures. The tipples usually are enclosed to protect equipment and men from the elements, and the most recently erected tipple has a heating system. At the other mines the men provide small heating units at their stations, usually small electric heaters.

Although overburden is stripped in the pit on a 24-hour basis, the lignite is loaded in 1 shift. The number of cars loaded during the shift depends upon market demand and to some extent the number of cars available. During the summer, the loading scheduled is reduced to 2 or 3 days a week or less. During the winter, when demand is high, loading schedules usually are on a more uniform daily basis. However, temporary car shortages during the heavy winter season frequently affect loading. Loading capacities of the tipples, as reported by the various mine operators, vary from 40 to 60 cars per day or about 2,000 to 3,000 tons. Gondola cars are in most common use; however, it is the practice to load lump coal for local domestic markets in boxcars.

From 12 to 18 men are employed in the larger tipples. The number is influenced by the demand for domestic sizes, since each car requires a man to operate the loader. During the winter extra labor is required to remove snow from cars, clear the tracks, and move the cars.

Description of Tipples

The newest tipple is operated by the Dakota Collieries Co. at Zap, N. Dak. It was erected and equipped by McNally-Pittsburg Co. in 1951 with a loading capacity of 300 tons per hour. Porter (25) described the installation as a 3 track tipple designed to produce a comparatively large percentage of domestic lump size. A schematic flow diagram for this tipple is shown in figure 24. The use of a loading boom permits double loading on one track. Sizes produced at this tipple are 6- by 3-inch furnace, 3- by 2-inch stove, 2- by 1-1/2-inch nut, 1-1/2- by 1/2-inch stoker, and the 1-1/2- by 0-inch screenings. The products may be oil treated during loading.

A larger tipple, built in 1945 at the Dakota Star mine, Hazen, N. Dak., was designed to supply a heavy load of the industrial sizes. The flow diagram of this tipple is shown in figure 25. A photograph of the tipple during winter operations is shown in figure 26. The entire output of this mine may be crushed to a 2- by

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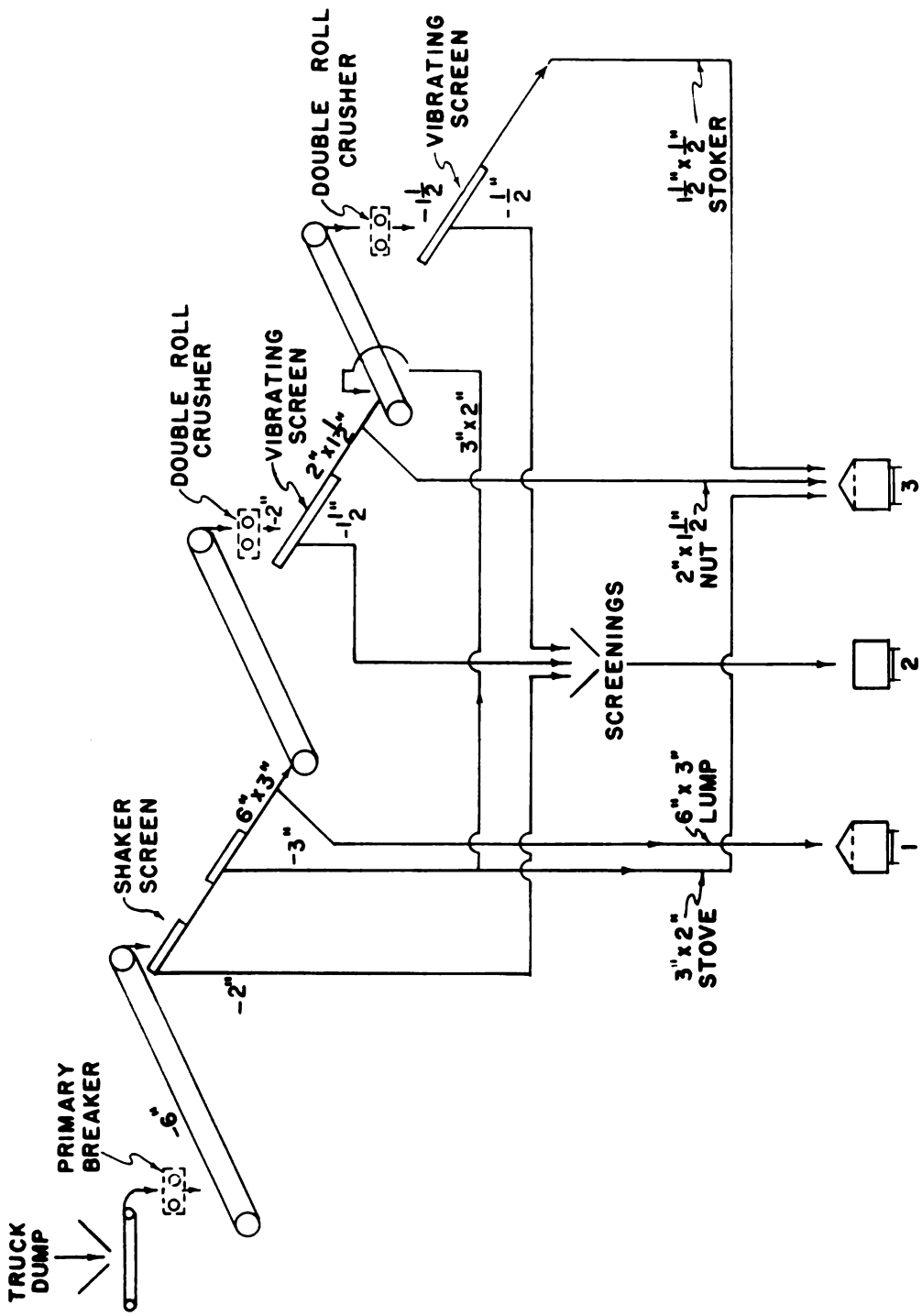

Figure 24. - Tipple flow diagram, Dakota Collieries mine, Zap, N. Dak.

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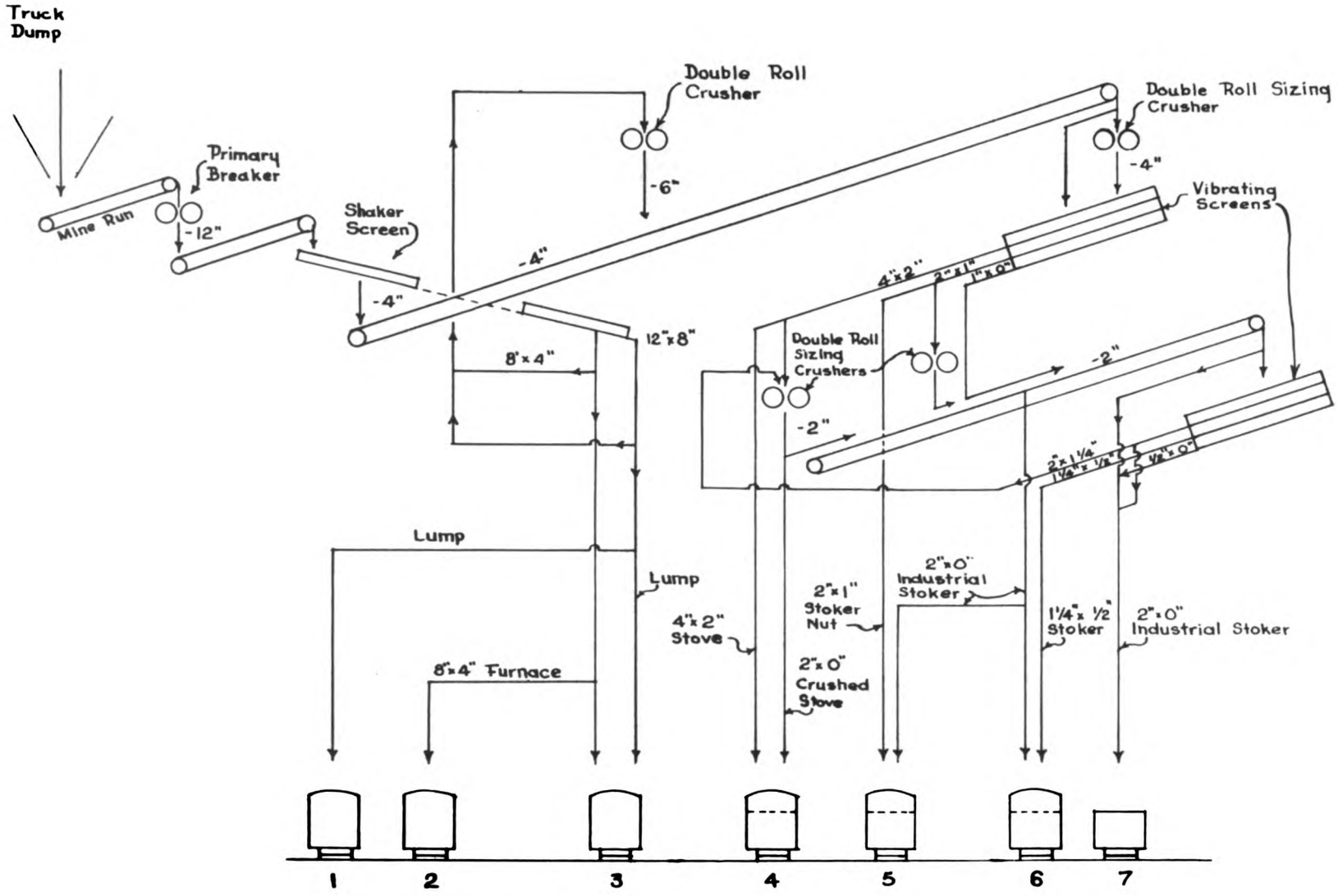

Figure 25. - Tipple flow diagram, Dakota Star mine, Hazen, N. Dak.

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Figure 26. - Modern tipple, Dakota Star mine, Hazen, N. Dak.

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0-inch size, with no reduction in capacity. The seven loading tracks provide adequate facilities for loading both domestic and stoker sizes during winter. The mine superintendent reports that a maximum of 4,400 tons has been loaded in 1 shift (7 hours, 15 minutes). In addition to the large domestic sizes, 2- by 0-inch crushed, 2- by 0-inch screenings, 1-1/2- by 1/2-inch stoker, and 2- by 1-inch nut sizes are produced. Both industrial and domestic stoker sizes may be oil treated.

Pulverizing

The new W. J. Neal station of the Central Power Electric Cooperative, Voltaire, N. Dak., is designed to burn pulverized North Dakota lignite. Installation of this type of burning equipment in the newest and largest station is significant because of the present successful, widespread use of spreader-stoker-type equipment. The selection of pulverized burning equipment was influenced by successful operation of a pulverized system using lignite by the Otter Tail Power Co. in one unit of its Crookston, Minn., station. These two stations are the only installations using pulverized burning equipment in this region.

At the Crookston station two No. 5 Riley Attrita unit pulverizers are used to fire one boiler, while another similar boiler is fired with a spreader stoker. The performance of these pulverizers was observed during a cooperative boiler test conducted at the Crookston station by the Bureau of Mines staff, Grand Forks, N. Dak., the Otter Tail Power Co., and the engineering staff, University of North Dakota. The test was designed to compare the performance of the boiler using natural lignite in one test and steam-dried lignite in the other at the same loading. The different feed rates, the different feed sizes, and the operation of the pulverizers at a relatively low rating did not permit a satisfactory comparison of typical operation or power consumption of the pulverizers upon the two different fuels. The data that were taken are of value, however, in indicating the size-reduction performance of the pulverizers (11). The feed rate to the pulverizers during the test with raw lignite was 6,670 lb. per hour of 1-1/2- by 3/8-inch stoker lignite. During the comparative test on the 3/8- by 0-inch, steam-dried lignite, the feed rate was reduced to compensate for the higher heating value of this fuel. The average feed rate was 5,050 pounds per hour with steam-dried lignite. Comparative screen analyses of the pulverized fuels are tabulated in table 12. The steam-dried lignite was pulverized to a greater degree of fineness; although, when the feed size is considered, the size reduction was greater on the natural lignite. The temperature of the primary air also was adjusted to compensate for the reduced moisture content of the steam-dried lignite: 616° F. for the natural lignite of 32.5 percent moisture content and 497° F. for the steam-dried lignite of 15.6 percent moisture content. The amount of drying in the pulverizers is indicated by the moisture content of the pulverized product: 19.1 percent for the natural lignite and 7.9 percent for the steam-dried lignite. Since primary air is used for drying in the pulverizers, the moisture removed is carried into the furnace. The mixture of air and pulverized fuel entered the furnace at 143° F. during the natural lignite test and 187° F. during the test of the dried lignite. The power consumption of the pulverizers during the test periods is tabulated in table 13.

Less power per ton of feed was consumed for pulverizing the natural lignite; however, on a heat value basis, the power consumption was less for the steam-dried lignite.

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TABLE 12. - Size distribution of pulverized lignite from No. 5 Riley Attrita unit pulverizer[1]

Test No.		1		2	
Date		10/9/49		10/16/49	
Type of lignite		Natural		Steam dried	
Sieve size		Differential percent retained on screen	Cumulative percent passed by screen	Differential percent retained on screen	Cumulative percent passed by screen
U. S. number	Opening, inches				
16	0.046	0.4	99.6	0.1	99.9
30	.0232	1.9	97.7	.7	99.2
50	.0116	10.3	87.4	4.0	95.2
100	.0058	23.5	63.9	17.5	77.7
140	.0041	10.8	53.1	13.1	64.6
200	.0029	15.0	38.1	11.1	53.5
Not retained		38.1	-	53.5	-

1/ Results are the weighted average from 20 samples, 10 from each burner feed pipe.

TABLE 13. - Power consumption for lignite in a No. 5 Riley Attrita unit pulverizer

Test No.	1	2
Type of lignite	Natural	Steam dried
Feed rate, lb./hr.	6,670	5,050
Heating value, B.t.u. per lb.	7,270	9,170
Power consumption, kw.-hr./hr.	71.2	60.3
Power consumption, kw.-hr./ton	21.3	23.9
Power consumption, kw.-hr./million B.t.u. in lignite	1.47	1.30
Feed rate, lb./hr. of moisture-free lignite	4,502	4,262
Power consumption, kw.-hr./ton of moisture-free lignite	31.6	28.3

Six Raymond bowl mill pulverizers with a rated capacity of 20,000 pounds of lignite per hour each have been installed at the W. J. Neal station, Voltaire, N. Dak. Three units serve each of the two boilers. The feed lignite, containing 38 percent moisture, is crushed to minus-3/4-inch before pulverization. During the acceptance test of the boilers at 100 percent load rating, the average feed rate to each mill was 17,740 pounds per hour. Primary air entered the pulverizers at 686° F., and the air and pulverized-fuel mixture entered the furnace at 130° F. Assuming an 80-percent efficiency for the electric motors, the power consumption of the pulverizer units, operating at 100-percent boiler load rating during the test, was 12.7 kw.-hr. per ton of lignite pulverized.[2] Samples of the pulverized fuel were not taken.

This station has also incorporated several features to facilitate handling of the lignite, maintain even flow to the pulverizers, and lower the power requirements of the pulverizers (7). All exterior unloading hoppers are lined with heating coils, and the station has installed a system of bunker heating. The bunker heating system and the pulverizing units are shown in figure 27. During winter the frozen lignite, ice, and snow thaw in the bunkers, and the resulting wet material does not flow. To avoid this difficulty, air at 400° F. is introduced into the bunkers near the bottom discharge to the feeders. It has been found that best results are obtained by refilling the bunkers directly over the discharge outlet. This procedure concentrates the fines directly over the outlet and in a better position for contact with the hot air.

2/ Data from a letter written by E. Wicklund, W. J. Neal station, Central Power Electric Cooperative, Inc., Voltaire, N. Dak., 1953.

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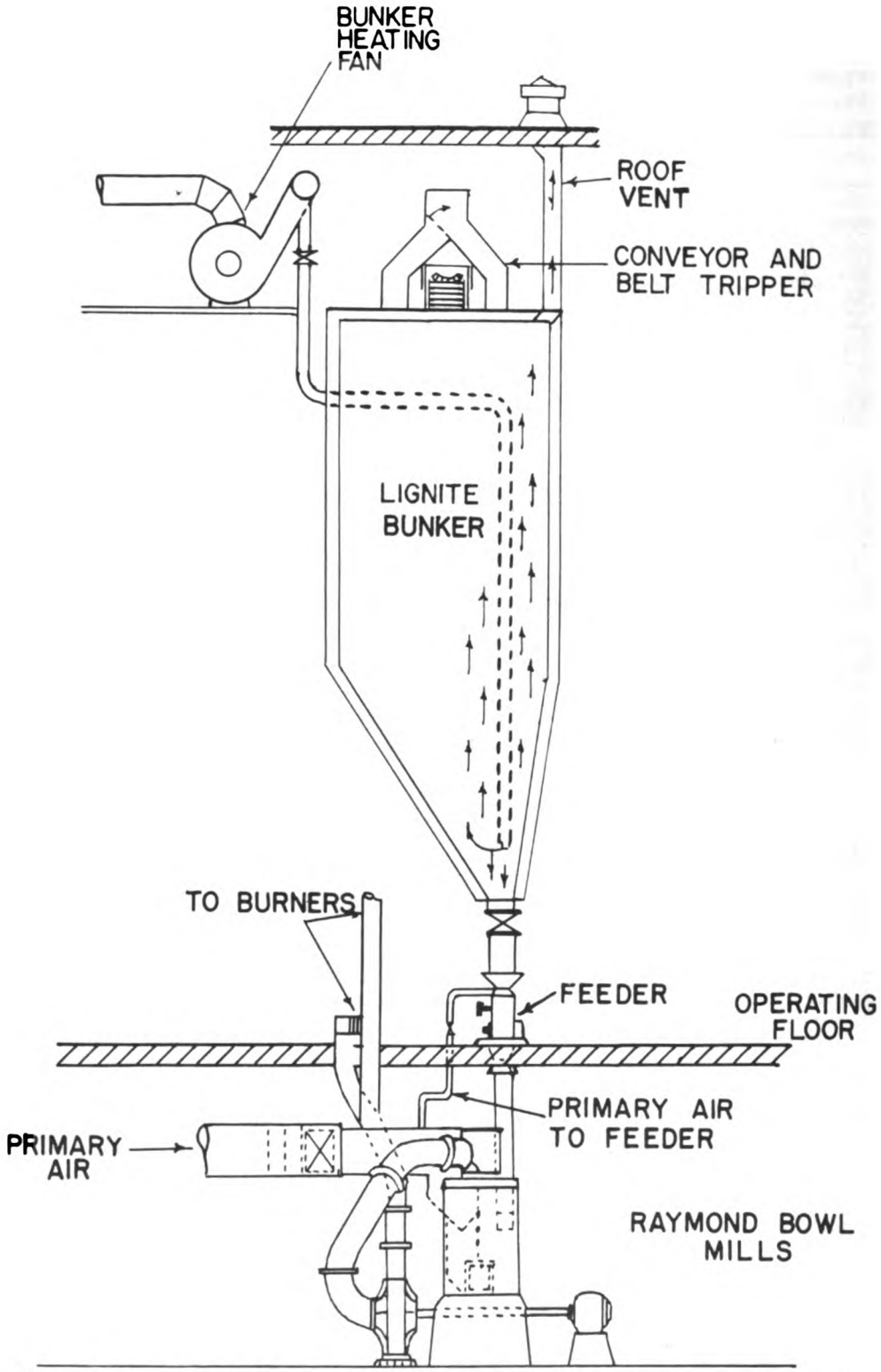

Figure 27. - Bunker heating system and pulverizers, W. J. Neal station, Central Power Electric Cooperative, Voltaire, N. Dak.

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The coarse material flows along the sloped edge of the bunker to the feeder more readily than the smaller particles. Use of the bunker heating system has proved quite successful and has eased the difficulty of handling lignite during the winter months.

Grindability of Lignites

In comparison with other coals, few determinations of grindability of lignite are reported in the literature. The 1954 Manual of Industry Standards and Engineering Information published by the American Boiler and Affiliated Industries (1), reports a Hardgrove grindability of 50 for one sample of North Dakota lignite. To increase the information available on the grindability of lignites, tests have been carried out at the Lignite Research Laboratory, Bureau of Mines, Grand Forks, N. Dak.3/ Samples of lignite of different moisture contents have been tested according to standard procedure ASTM D409-47T (2, pp. 620-623). The grindability indexes of the samples tested ranged from 37 to 81. The effect of moisture on grindability is illustrated in figure 28. Samples of each lignite, crushed to minus-1/8-inch, were exposed in the laboratory at normal room temperature or in a standard air-drying oven at 150° F. to obtain samples in the complete moisture content range. Following the reduction in moisture content, the samples were prepared to the size specifications used in the standard test. In the Hardgrove test machine, a fixed weight is applied to the grinding race and rotated a specified number of times, but no measurement is made of the torque (or power) required to produce a given size reduction. Even though high grindability is shown for a high-moisture-content sample, as indicated in figure 28, this may not be the most advantageous condition under which to pulverize lignite when power requirements are considered. The smearing or caking of the pulverized particles in the machine has been found to be greatest at the higher moisture contents, and in practical operation, this would result in considerable difficulty in both pulverizers and burners.

Power Requirements of Pulverizing

The power required to pulverize bituminous coals is reported to range from 9 to 17 kw.-hr. per ton, depending upon grindability, moisture content, and final particle size (15). On a comparable heating value basis, the power required to pulverize lignite is higher. On a weight basis, the estimated power requirements for lignite pulverizing at the Voltaire station as presented earlier (approximately 13 kw.-hr. per ton) fall within the above range. Directly comparable power-requirement data for lignite and for bituminous coals at the same degree of size reduction are not available. In general, lignite need not be ground as fine as high-rank coals for pulverized firing. Some additional shattering of the lignite particles is obtained through rapid moisture vaporization and release when the particles enter the furnace. In practice, preheated primary air is used to partly dry the lignite in the pulverizers. Although all moisture removed in the pulverizers is carried to the burners with the fuel and air, operating experience has demonstrated that stable ignition is readily obtained.

Drying

The moisture content is the dominating factor influencing the use of lignite as a fuel. The removal of moisture from lignite is accompanied by a marked increase in heating value per unit weight. By removing moisture at low cost, the area in which lignite may be economically used could perhaps be extended and savings in transportation cost realized within the present consuming area. In direct heat drying with hot flue gases, considerable size degradation occurs. Consequently, the most promising

3/ Data recorded at the Bureau of Mines laboratory, Grand Forks, N. Dak.

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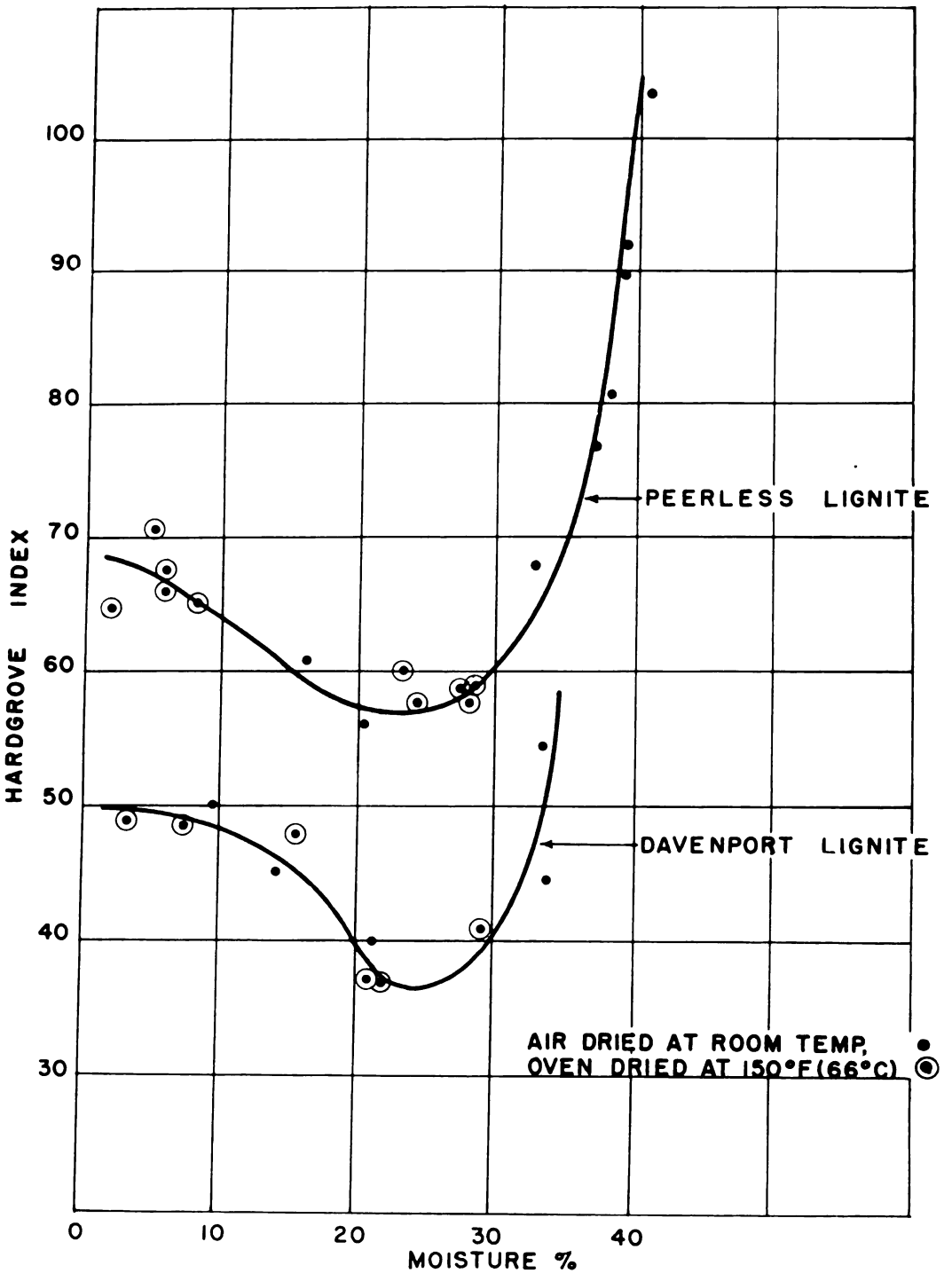

Figure 28. - Variation in grindability index of lignite with varying moisture content of sample.

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processes of this type have been developed for use with fine-particle fuel, so-called entrained or fluidized drying. By heating lignite in an atmosphere of saturated steam, followed by pressure release and moisture evaporation, the size degradation accompanying the drying process can be greatly reduced. This steam drying process makes it possible to obtain lump lignite of low moisture content and high heating value.

Steam Drying

Lignite has been steam-dried commercially in Europe; but, owing to different economic conditions, this method has been used in the United States on an experimental scale only. In countries where lignite is the only source of solid fuel, steam drying has proved to be an economical method of upgrading lignite. Two views of a commercial steam-drying plant now in operation in Koflach, Austria, are shown in figure 29.

Lignite is degraded during all types of drying, but slacking is greatly reduced when steam drying is used.

The process of steam drying is as follows: Lignite is placed in an autoclave and heated with saturated steam. Steam pressures of 250 to 400 p.s.i.g. are normally used. The period of steam addition is referred to as the heating period and is followed by a steaming period during which time the pressure is maintained. The steam supply is then shut off and the pressure released.

The process involves heating the raw lignite in an atmosphere of saturated steam until each lump is thoroughly heated. Since saturated steam is used, water does not evaporate. During the heating and steaming periods, however, some of the moisture in the lignite is expelled and drained off as liquid water. Release of water is accompanied by shrinkage of the lignite particles. The removal of water as a liquid is due to a change in the structure of the lignite. The high temperatures used probably cause the cells to collapse, producing conditions favorable for removing moisture. By this action, the lignite retains its original shape, and no excessive size degradation takes place. The residual heat in the lignite causes additional moisture to be removed during the pressure-release period, further reducing the moisture content. Since part of the water is removed as a liquid, thermal requirements for steam drying, per unit quantity of moisture removed, are less than for drying processes in which all moisture is removed by vaporization.

Extensive experiments have been carried out by the Bureau of Mines and the University of North Dakota on steam-drying subbituminous coal and lignite (6, 13, 22, 23).

Equipment used in experimental work by the Bureau of Mines is shown in figure 30. The following summarizes the conclusions reached on the basis of these experiments:

(1) The amount of water removed depends upon the temperature to which the lignite is heated. With increase in temperature, more moisture is removed as a liquid, and more moisture is evaporated during the pressure release period, owing to the higher residual heat in the lignite.

(2) The time required to heat the lignite, which determines the length of the steaming period, is independent of the final temperature but dependent upon the size of the lignite particles. An approximation is given by the equation $t = 7D^2$, where D is the diameter of the particle in inches and t is the time in minutes.

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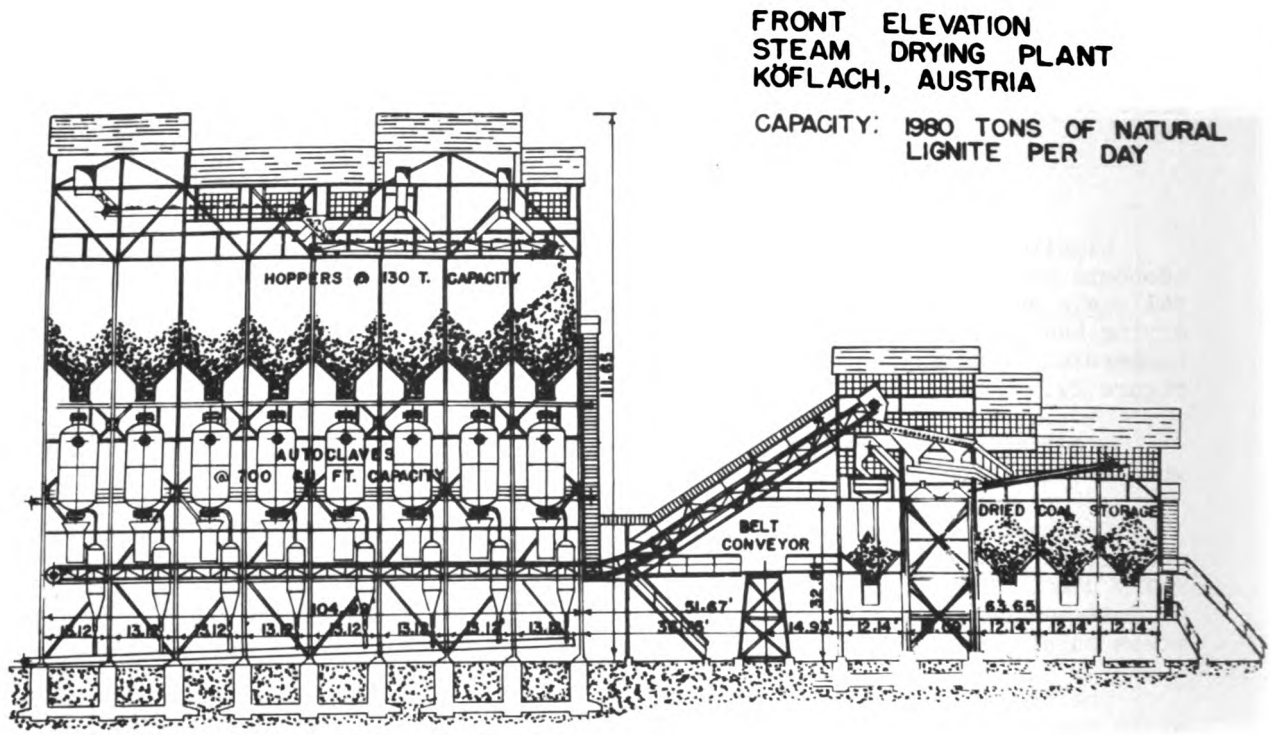

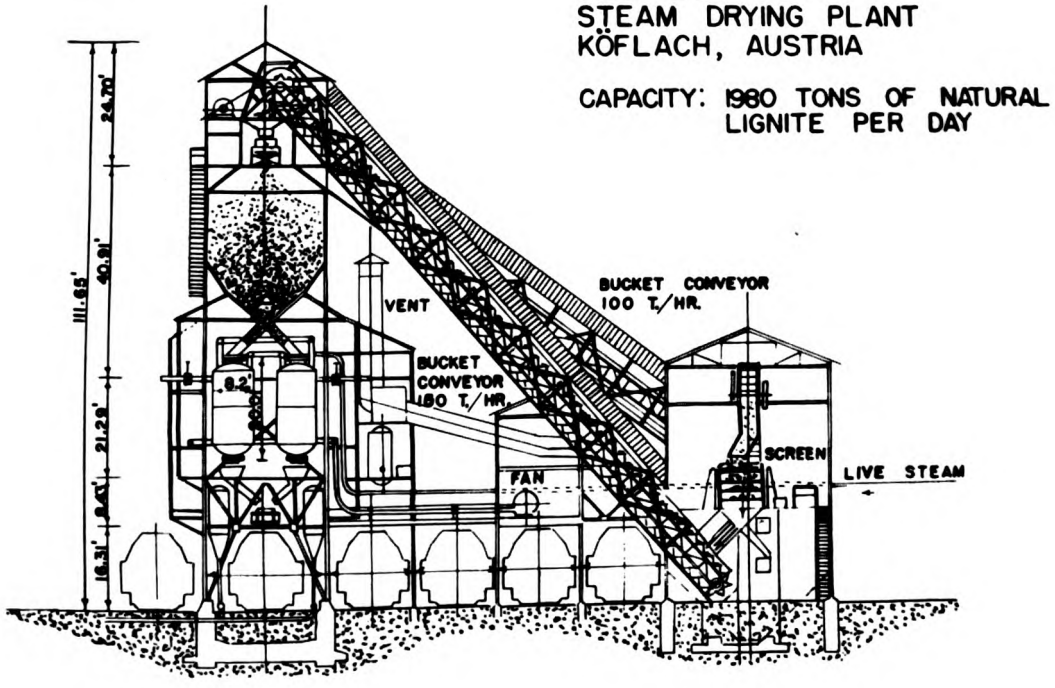

Figure 29. - Front and side elevations of steam-drying plant, Köflach, Austria.

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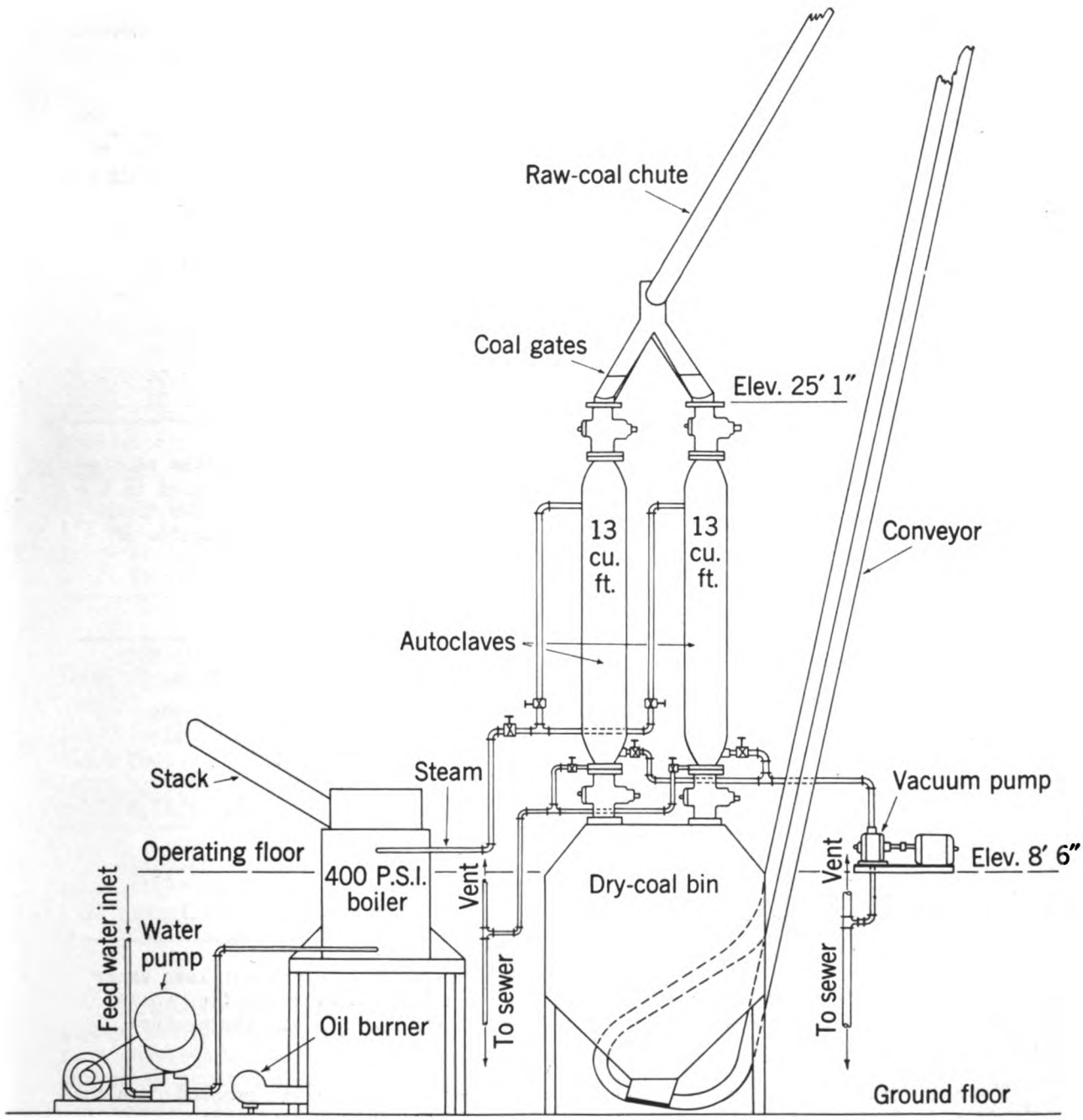

Figure 30. - Pilot plant for steam-drying subbituminous coal and lignite, Bureau of Mines, Grand Forks, N. Dak.

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(3) No relationship exists between pressure used and degradation of the lignite; however, the percentage of size reduction is greater when larger sizes are dried. Differences are noted between different lignites when treated at the same pressure. Representative data on size degradation are presented in table 14.

TABLE 14. - Size degradation of lignite in steam drying

Lignite	Pressure, p.s.i.	Average size of feed, inches	Average size of product, inches
Coteau bed	200	3	2.49
Do.	400	3	2.46
Do.	200	1.25	1.01
Do.	400	1.25	1.01
Noonan bed	200	3	1.72
Do.	400	3	1.87
Do.	200	1.25	1.04
Do.	400	1.25	1.07

Percentage of moisture removed as a liquid may vary widely for lignites of similar initial moisture content. Differences exist even between lignites mined in the same general area. In table 15 data reported by the Bureau of Mines for two North Dakota lignites (16) are listed and compared with data for an Austrian lignite of similar initial moisture content (12).

TABLE 15. - Moisture removed during steam drying

Lignite	Austrian	Dakota Star mine, Hazen, N. Dak.	Kincaid mine, Columbus, N. Dak.
Pressure..... p.s.i.a.	280	300	300
Temperature..... °F.	411	417	417
Initial moisture content...percent	37.0	34.8	34.5
Water removed as a liquid..... .....percent of initial moisture	46.0	26.7	17.1
Water removed, including pressure release period..... .....percent of initial moisture	70.2	57.3	49.8
Final moisture content after pressure release period..percent	14.9	18.4	21.0

Table 15 shows that, for the same processing conditions, 36 percent less water was removed as a liquid from Kincaid lignite than from Dakota Star lignite, while the Austrian lignite, processed at slightly lower steam pressure and temperature, released 80 percent more.

The net steam consumption in pounds of steam per pound of water removed from the North Dakota lignites was 0.65, 0.63, and 0.71 pounds for Dakota Star and 0.71, 0.72, and 0.85 pounds for Kincaid at pressures of 370, 300, and 200 p.s.i.a., respectively (16). These figures include moisture removed during a 24 hour period of aeration of the dried product. Approximately 15 percent of the original moisture is removed during the aeration. The final moisture content, after the aeration period, varied from 12 percent at 370 p.s.i.a. to 20 percent at 200 p.s.i.a. Under the climatic conditions prevailing in North Dakota (average relative humidity 50 percent), lignite, steam dried to a moisture content of 12 percent, will absorb moisture in

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storage until the equilibrium moisture content is reached, at 15 to 18 percent. Therefore, if the lignite is not to be used immediately upon drying and is to be stored or shipped in open cars, there is no incentive for drying to less than equilibrium moisture content.

Rotary Drying

Data have been obtained by the chemical engineering department of the University of North Dakota on the experimental drying of lump lignite in a Roto-Louvre-type rotary drier.[4] In this drier, the heated gases are passed through the bed of lignite from ports in the inner shell. Because material to be dried is not lifted and dropped through the gas stream as in conventional rotary drying, size degradation should be less than for conventional driers. A maximum inlet temperature of 1,000° F. was used in the experimental work. Outlet temperatures varied from 140° F. to 190° F., depending on the degree of drying. Results are summarized in table 16.

TABLE 16. - Drying of lignite in Roto-Louvre drier

Feed size, inches	Moisture in feed, percent	Moisture in product, percent	Heat input, b.t.u./lb. water evaporated	Feed rate, lb./hr.
1-1/2 by 1/2.....	33.6	20.2	2,460	965
1/2 by 0.....	32.0	18.6	1,900	1,320
1-1/2 by 1/2.....	36.4	12.8	2,150	640
1-1/2 by 1/2.....	33.3	10.2	2,330	977

Size degradation in Roto-Louvre drying

Feed size, inches	Moisture in product, percent	Portion of product through 4-mesh (0.185 inch), percent
1-1/2 by 1/2.....	19.4	29
1-1/2 by 1/2.....	20.2	31
1-1/2 by 1/2.....	14.3	57
1-1/2 by 1/2.....	15.1	59

Although the rotary drier offers the advantages of continuous operation and control, capacity and overall heat efficiency are low. Size degradation is far over that prevailing in steam drying.

Fluidized Drying

Since the low-rank coals tend to break down in size on direct drying with flue gases, the obvious applications for processes of this type are in the treatment of fine particles. Excellent contact and high capacity can be achieved by fine-particle drying in the entrained and fluidized state.

Entrained drying can be used for removing either surface or inherent moisture. Originally, this method of drying was employed to remove surface moisture on washed coal to prevent freezing during the winter and in the preparation of coal fines for briquetting. More recently, fine-particle drying in the entrained state has been used to remove inherent moisture from subbituminous coal and lignite.

4/ Data from University of North Dakota, Chemical Engineering Dept., Grand Forks, N. Dak.

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Raymond Flash Drier

Entrained drying dates back to 1930 when the Raymond flash drier was developed (9). In this drier, illustrated in figure 31, hot gases generated in the combustion chamber are tempered with air and passed into the drying column, into which pulverized coal is also fed continuously. Intimate contact of the hot gases and the small coal particles promotes rapid heat exchange and drying. The mixture of gases and fine coal is carried into cyclone separators, where the dried product is recovered.

The combustion chamber or air heater is in most instances fired by automatic stoker. The mixture of air and products of combustion enters the drying column at 1,000° F. and leaves the column at about 150° F. Depending upon the material to be dried, retention time varies from 1 to 10 seconds. Since the coal is carried by the gas stream, entrained drying is limited to the smaller sizes. About 3/8 inch is the largest size that can be dried successfully.

Commercial driers of this type handle 15 to 75 tons per hour of 1/4- by 0-inch coal and dry the product from 12 percent initial moisture to 3 percent final moisture. Driers are designed for drying materials with a maximum surface moisture of 25 percent. When coals with high surface moisture are dried, a portion of the dried product must be recycled to obtain uniform feed distribution and control.

Entrained Drying, Bureau of Mines, Denver, Colo.

Over the last several years, extensive experimental work has been carried out by the Bureau of Mines, Denver, Colo., on removing inherent moisture from subbituminous coal and lignite by entrained drying (19, 20, 21, 24). When inherent moisture is removed from the low-rank coals, air cannot be used in the drying column, since combustion of the coal would result. Bureau of Mines development of entrained drying of low-rank coals has been based on recycling the products of combustion to furnish an inert gas. With this technique, inlet temperatures to the drying column as high as 2,100° F. have been used successfully. Heat exchange is very rapid and high capacities are obtained.

Bureau of Mines experimental unit for entrained drying of subbituminous coal and lignite is illustrated in figure 32. Because of high capacity and low heat loss, heating efficiencies of 80 percent have been obtained in experimental units, and efficiencies over 90 percent are expected with commercial-size driers. A dried product with a moisture content of 5 percent or lower is readily recovered. Data obtained in drying Texas lignite (20) are shown in table 17.

TABLE 17. - Entrained drying of Texas lignite

	Before drying	After drying
Moisture..... percent	39.2	3.4
Heating value.....B.t.u./lb. gross	6,380	10,200
Heating value.....B.t.u./lb. net	5,740	9,760
Average sizes.....inches	0.037	0.020
Gas inlet temperature.....°F.	2,105	
Gas outlet temperature.....do.		300

Fine-particle lignite dried to low moisture content is highly subject to spontaneous combustion and can be safely stored or transported only in the absence of air. In addition, moisture regain on exposure to air is rapid, under normal

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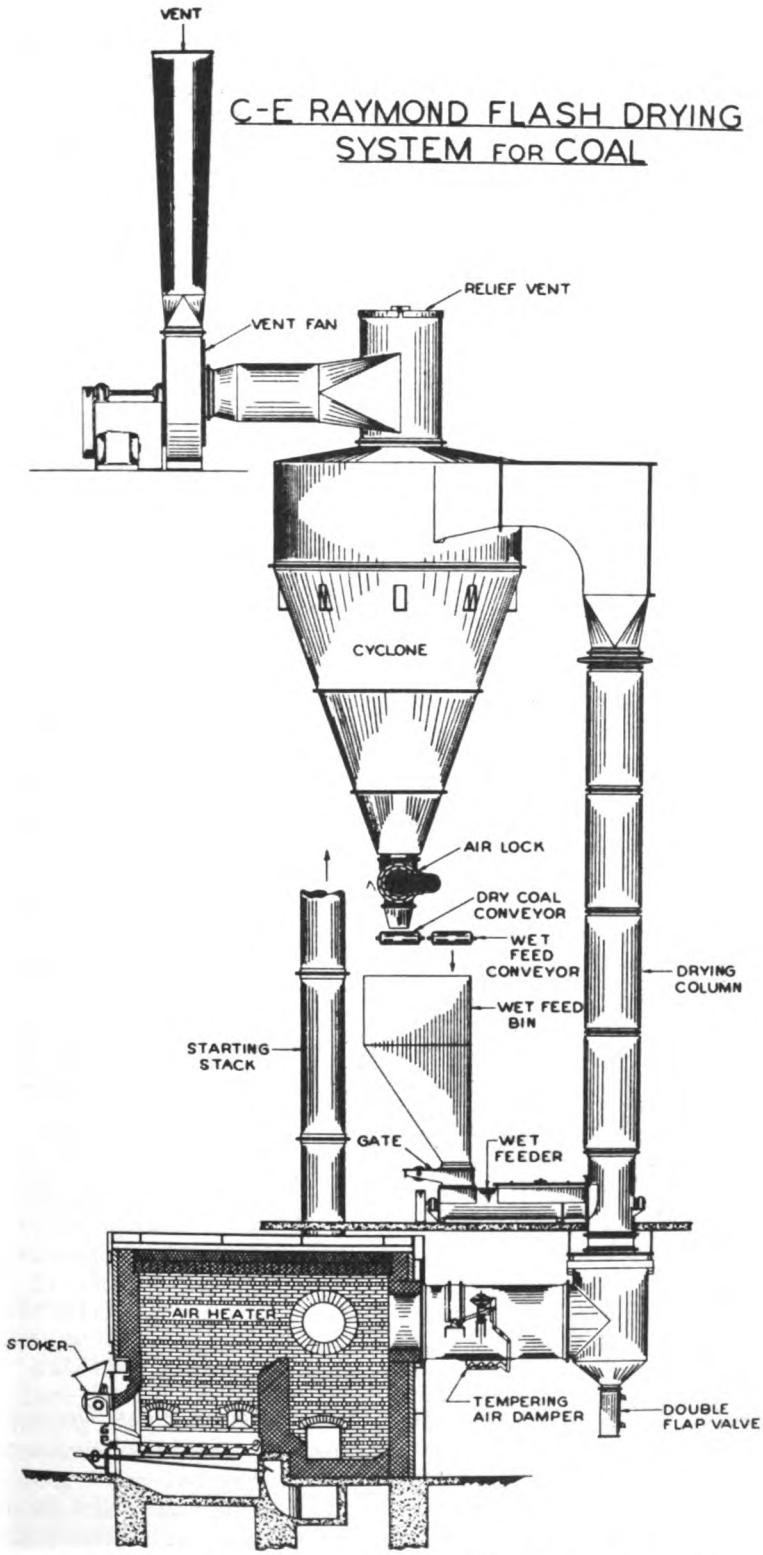

Figure 31. - C-E Raymond flash-drying system for coal.

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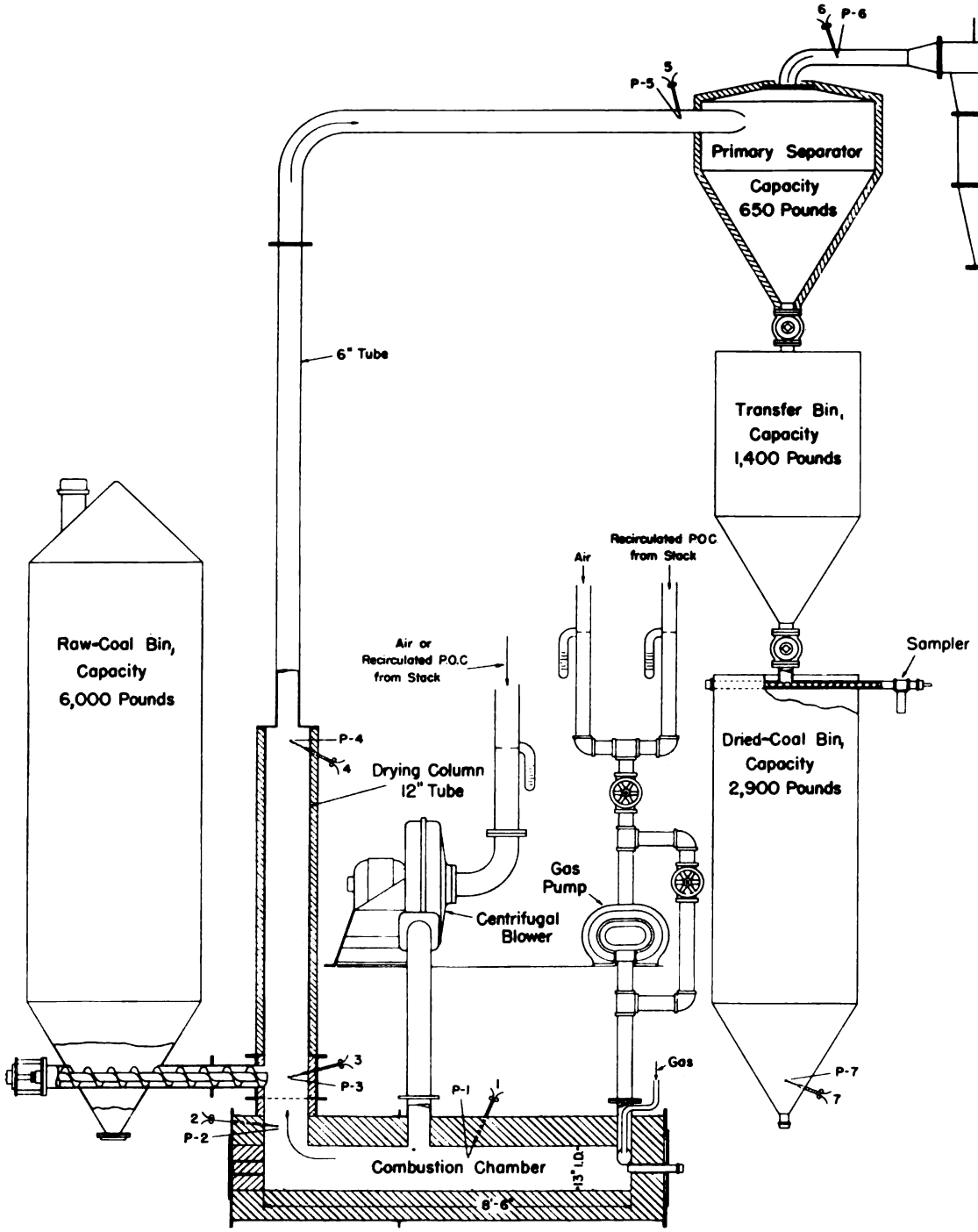

Figure 32. - Pilot plant 6 to dry fine coal, Bureau of Mines, Denver, Colo. Capacity 400 pounds moisture evaporated per hour.

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atmospheric conditions. Logical use of this product is therefore direct utilization in boiler plants or other processing. Entrained drying will be used to prepare lignite for subsequent carbonization by fluidized methods at a large plant now under construction at Rockdale, Tex. (14). Fluidized carbonization techniques are discussed in section 2, Part 2.

Briquetting and Pelletizing

Solid fuels are briquetted or pelletized to utilize waste fines profitably or to reconvert coal degraded in size by drying or carbonization into a lump product. Binding agents are normally required. Various binding agents have been used, including asphalt, pitch, starch, lignin, cement, plastics, and sulfite liquor (5). The major use of briquets is for domestic heating, although some briquets are used commercially in stationary stokers or in locomotives.

In the United States a peak production of some 3 million tons of briquets was reached in 1947. Briquets produced from lignite represent approximately 1 percent of this total production.

Commercial Production of Lignite Briquets

At present, the only commercial producer of lignite briquets in the United States is the Dakota Briquet & Tar Products, Inc., Dickinson, N. Dak. At this plant, lump lignite is carbonized in Lurgi-Spülgas retorts, described in section 2, Part 2. After carbonization, the cooled char is passed over a 1-1/4-inch bar screen to remove nondisintegrated lumps of iron pyrite and crushed in a Williams hammer mill to 1/8-inch maximum size (10). Heated binder is sprayed on the crushed char in a preliminary mixing drum, and final mixing takes place in a kneading machine or fluxer. The thoroughly mixed material is then formed into briquets in a Komarek-Greaves press. The fresh 3-1/2-ounce briquets are transported on a wire-mesh cooling screen to slotted storage bins for further aging and cooling.

The binder used is a mixture of lignite pitch and oil asphalt. During the summer, binders with a higher softening point are used. Of the 7 to 9 percent binder required, about one-third is lignite pitch obtained from the carbonization process. The briquets have enough strength and abrasion resistance for satisfactory commercial use. Burning and storage characteristics are also excellent. However, since briquets are used principally for domestic heating, production has been influenced by the general decline in the domestic market for solid fuels. Production of lignite briquets in 1952 was about 30,000 tons.

Experimental Production of Lignite Briquets and Pellets

The successful pressure briquetting of dried German brown coal without artificial binder led to similar experimental attempts to briquet United States lignites. Attempts to produce satisfactory briquets from United States lignites by pressure alone did not yield a commercially satisfactory product. Wright found that lignites from North Dakota, Texas, and California could be briquetted without binder when the natural bitumen material soluble in carbon disulfide exceeded 1.5 percent. These briquets were superior to the natural lignite but, with the possible exception of a lignite from Ione, Calif., weathered excessively and did not sufficiently retain their shape during combustion (27). Improved characteristics could be obtained with artificial binders; however, even with a binder, briquets of commercial quality could not be made from low-rank coals, including subbituminous coal, without excessive addition of binding agents (18). Apparently carbonization of low-rank coals is required to produce acceptable briquets.

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Recently, preliminary work has been carried out by the Bureau of Mines, Grand Forks, N. Dak., on pelletizing dried lignite by agglomeration with added binder in a heated rotary drum. This process is intended to control moisture regain of dried lignite and to produce, from fine-particle dried material, an agglomerated lump product that is suitable for shipment by conventional means.

Experimental results to date have shown that pellets with a low-moisture regain can be obtained (17). However, excessively large amounts of binder were required. Future promise is considered to depend on reducing binder requirements by developing a rapid processing technique, which will prevent excessive binder absorption and make maximum use of binder for surface coating and agglomeration.

Other Preparation Techniques

Reduction of Mineral Matter

Up to the present there has been no economic justification for the reduction of mineral matter in lignite by washing methods. Lignite, as mined, usually has an ash content between 5 and 8 percent. Removal of the weathered layer on top of the uncovered bed before loading and the practice of leaving the bottom of the bed as a floor for the loading shovel reduces the inclusion of extraneous mineral matter. Partings are found in several beds being mined, but they are usually quite thin and not extensive. The quality of the lignite for a given mine therefore is quite uniform.

Efforts have been made at several mines to improve the quality of lignite by operating hand-picking tables in the tipple. The lignite produced by one of these mines contains a relatively high amount of sulfur in the form of discrete lumps of pyrites, and sulfur content was reduced by operating the tables. In general, the mineral matter of lignite is largely composed of finely divided particles. To liberate these particles it is necessary to employ considerable size reduction. The separation of these particles of mineral matter is difficult, and improvement by gravity separation is slight.

A Bureau report gives washability data on a lignite sample from an underground mine, which has since closed, the Burleigh mine, Wilton, N. Dak. (8). The initial ash content of this sample was 7.8 percent. The report states:

> The amount of 1.50 specific-gravity sink material, usually considered to be extraneous high ash matter, is negligible. A rejection of 50 percent of the raw feed as refuse would result in an ash reduction of 1 percent in the clean coal. These studies indicate that the lignitic coal is not amenable to washing except for possible rejection of extraneous material included with the lignite during the mining phase.

The large amount of mineral matter normally concentrated in the fines indicates that mineral matter might be reduced by removing the smaller sizes. Several tests of a sample of waste slack from one of the major producing mines in North Dakota show the variation in ash content with respect to size.5/ Results of this test are given in table 18. The variation in ash content on the moisture-free basis ranged from 5.2 percent in the plus-3/4-inch fraction to 24.3 percent in the minus-200-mesh. By rejecting 49.1 percent of the material, a reduction in ash content from 15.4 percent to 13.2 percent could be achieved. In spite of the wide variation of ash content for the different size fraction, the improvement of this material by screening is not great, owing to the high percentage of the sample in the mid-ash content range.

5/ See footnote 3.

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TABLE 18. - Size-consist test data of Baukol-Noonan lignite screenings

Size	Moisture, percent	Weight-percent	Ash, 1/ percent	Cumulative weight, percent	Cumulative ash, percent
On 3/4-inch.....	26.4	3.1	5.2	3.1	5.2
On 1/2-inch.....	25.5	2.5	9.8	5.6	7.4
On 3/8-inch.....	23.7	3.2	7.5	8.8	7.4
On 4-mesh.....	22.5	13.8	13.2	22.6	10.9
On 8-mesh.....	23.8	28.3	15.0	50.9	13.2
On 14-mesh.....	23.7	22.4	16.1	73.3	14.1
On 28-mesh.....	24.4	12.2	16.3	85.5	14.4
On 48-mesh.....	22.8	6.4	18.6	91.9	14.7
On 100-mesh.....	23.7	3.6	21.9	95.5	15.0
On 200-mesh.....	22.2	2.3	23.1	97.8	15.2
Through 200-mesh..	20.1	2.2	24.3	100.0	15.4

1/ Moisture-free basis.

In a similar study conducted at the University of North Dakota,6/ a sample from another mine was tested. The variation of ash content with size, calculated on a moisture-free basis, is illustrated in table 19. For this sample, float-and-sink tests also were made, and results of these tests are given in table 20. A reduction in ash content of 2.36 percent is obtained at a yield of 81.70 percent. Results of this test indicate that investment in a washing plant would not be justified for this material.

TABLE 19. - Size-consist test data of Zap lignite screenings

Size	Weight-percent	Ash, 1/ percent	Cumulative weight, percent	Cumulative ash, percent
On 3/8-inch.....	12.9	8.6	12.9	8.6
On 4-mesh.....	10.7	10.0	23.6	9.2
On 8-mesh.....	19.2	10.1	42.8	9.6
On 14-mesh.....	21.6	10.2	64.4	9.8
On 28-mesh.....	20.2	11.8	84.6	10.3
On 48-mesh.....	13.6	14.9	98.2	10.9
Through 48-mesh.....	1.8	17.8	100.0	11.0

1/ Moisture-free basis.

TABLE 20. - Float-and-sink data of 1-1/2-inch by 28-mesh sample of Zap lignite

Specific-gravity fractions	Weight-percent	Ash, 1/ percent	Cumulative weight, percent	Cumulative ash, percent
Float-1.25	2.7	5.9	2.7	5.9
1.25-1.31	58.8	7.0	61.5	6.9
1.31-1.35	20.2	8.8	81.7	7.4
1.35-1.41	11.2	13.0	92.9	8.0
Sink-1.41	7.1	32.0	100.0	9.7

1/ Moisture-free basis.

6/ See footnote 2.

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Use of Treating Agents

Loss of moisture during storage of lignite causes disintegration and formation of dust. Since domestic consumers have demanded greater convenience and ease of handling the mining companies have undertaken to improve lignite quality and reduce these undesirable characteristics.

Some increase in the use of oil to reduce the formation of dust has been noted. Along with reduction in dust, improvements in handling during winter as a result of oil treatment have been reported by coal dealers and industrial users. In usual practice 4 to 6 quarts of oil is sprayed per ton of lignite. During 1950, 7 mines reported oil-treating 92,803 tons of lignite, representing 5.5 percent of the total production for that year (3). In 1951 this was increased to 111,019 tons, or 6.0 percent of the total production. Mine operators have reported that oil treatment has enhanced the sales value of the product, particularly among domestic users. Substantial savings during the winter months have been reported by some industrial consumers through the use of oil on the stoker sizes to reduce the danger of the coal freezing in transit.

There has been no reported use of other treating agents, such as calcium chloride, to reduce dust and improve the handling qualities of lignite. Use of calcium chloride to reduce dust is not recommended for coals that have an inherent bed-moisture content of over 8 percent (26). Use of calcium chloride to reduce freezing in cars may be more promising, because freezing in cars is due in part to factors such as the mixing of snow and ice with the fines, in addition to surface moisture.

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6. STORAGE AND TRANSPORTATION

Storage

Storage of solid fuels is important to industry in that it assures an adequate fuel supply at all times, such as during transportation delays and production shortages. In addition, some users take advantage of lower freight rates during certain seasons of the year. For a consumer along or near the Great Lakes or inland waterways, fuel can be stockpiled at the plants or docks during the summer and enough fuel provided to last through the winter season, when the waterways are closed.

Storage of large quantities of solid fuels in outdoor stockpiles involves certain problems, the greatest of which is the possibility of spontaneous combustion. Most coals will ignite spontaneously under unfavorable storage conditions, the danger being greater for lower rank coals. Little or no care need be taken in storing anthracite, but strict storage procedures must be followed for subbituminous coal and lignite. Other disadvantages include slacking and loss in heating value during storage, effects which are also more pronounced for the lower rank coals.

Methods of Storage

Bins or silos are used for storage where small amounts of lignite are required (9, 12).[1/] When the lignite is continuously being removed and used, little difficulty is encountered in this type of storage. If the lignite is to be stored for longer periods, airtight covers can be used as a safety measure to prevent natural draft through the stored lignite.

Underwater storage of coal has been used in certain cases. This type of storage protects the coal satisfactorily against spontaneous heating, but initial cost and maintenance of the storage facilities are high.

For large tonnages, the most common method of storage now in use is stockpiling in compacted piles (1, 2, 3, 10). By the use of properly compacted storage piles, large tonnages of lignite have been successfully stored, with no difficulty from spontaneous ignition.

The area in which lignite is to be stored must have good drainage and should be thoroughly cleaned of all extraneous material. The lignite should be laid down with a minimum of size segregation, as separation of the various sizes will produce tightly packed and loosely packed sections, increasing the tendency toward spontaneous combustion. Lignite is placed on the ground in benches approximately 1 foot high and thoroughly compacted with a bulldozer or roller. Benches may be added, each one being similarly compacted until the desired height of the pile is reached. The height of the pile is limited only by requirements for convenience in handling and in reclaiming. The sides are also compacted and sloped at an angle of about 20°. Compaction of the lignite minimizes movement of air through the storage pile and thereby limits oxidation. When a storage pile is first put down, temperatures within the pile should be taken periodically to detect any local hot spots resulting from inadequate compaction. If hot spots do occur, these may in some instances be controlled, in the initial stages, by further compaction. If ignition has begun, however, this section of the pile must be removed.

Impervious layers of materials, such as asphalt, have been spread over the surface of some storage piles to seal the surface and prevent air circulation, but such treatment is not necessary in storing lignite.

1/ Underlined numbers in parentheses refer to citations in the bibliography at the end of this section.

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When exposed to normal atmospheric conditions, lignite loses part of its moisture. Under the humidity conditions prevailing in North Dakota, an equilibrium is reached at between 15 and 20 percent moisture. As the particles of lignite begin to dry, water is removed from the outer surface at a higher rate than it is replaced from the interior, resulting in shrinkage of outer surfaces. Stresses set up by this action cause the lignite surface to crack and disintegrate. If the lignite is moistened by rain, the outer surface expands again, causing a further breakdown. After repeated drying and wetting, the lignite on the surface of the pile will break down completely into fine particles. These fines serve as a protective coating and prevent air from entering the main body of the storage pile. In large storage piles, slacking penetrates only a few inches below the surface, and the main body of lignite is not affected. Experience in recent years with large-scale storage of lignite in compacted piles has demonstrated that, when the piles are correctly laid down, spontaneous ignition can be eliminated.

Spontaneous ignition can also be avoided in storing large and carefully screened sizes of lignite by providing for air circulation through the pile at a rate sufficient to remove heat generated. The oxidation rate is a function of the particle size, and since the surface area of large sizes is relatively small, oxidation proceeds at a relatively slow rate. When large sizes, with all fines removed, are stored without compaction, air can easily penetrate the main body of the storage pile, and the heat liberated by oxidation is effectively dissipated. The Bureau of Mines has used this method with satisfactory results to store plus-3/8-inch steam-dried lignite at Grand Forks, N. Dak.2/

The initial rate of heating is directly related to temperature at the time of storage; the higher the temperature the more rapid the rate of heating. Storage during the hot summer months greatly increases the possibility of spontaneous combustion. Therefore, care should be exercised in storing lignite during warm weather, and any hot spots that occur should be detected early and removed. Newly exposed surfaces, as in freshly mined or freshly crushed lignite, are most susceptible to oxidation. The rate of oxidation is at its maximum immediately after storage and decreases with time. Experience has demonstrated that, if spontaneous fires do not occur within the first 3 or 4 months, the storage may be considered safe.

Laboratory Investigation of Spontaneous Heating Tendencies

Laboratory-scale studies have been carried out at the University of Minnesota and the University of North Dakota on comparative heating tendencies of various coals by determining their critical oxidation temperature (6). Experimental procedure is as follows: A retort containing the coal sample is placed in a furnace heated at constant rate. Temperatures of the coal sample and the furnace are measured by thermometers or thermocouples. Oxygen is passed through the sample during heating, and the lag between the temperatures of furnace and sample is recorded. As the sample of coal begins to heat spontaneously, the temperature of the sample increases rapidly and approaches the temperature of the furnace. The temperature level at which the furnace and sample temperature are equal is designated as the critical oxidation temperature. Results of the tests showed that the higher rank coals have high critical oxidation temperatures. Temperatures, as determined, ranged from 257° C. for anthracite to 183° C. for lignite. Comparisons of lignites from 10 different mines in North Dakota showed no significant differences in critical oxidation temperature. Decrease in moisture content and in particle size resulted in lowering of critical oxidation temperature.

2/ Data on file at Bureau of Mines Laboratory, Grand Forks, N. Dak.

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A change in operating conditions - for example, increase in rate of oxygen admission - also changes the critical oxidation temperature. Thus the values obtained are useful for comparative purposes only.

Further investigations on the heating rates of coals were carried out by the Bureau of Mines, Pittsburgh, Pa.(7). Experimental apparatus is shown in figure 33. A sample of coal was placed in an adiabatic calorimeter in an atmosphere of nitrogen and heated to a predetermined temperature - 158° F. for subbituminous coal and lignite and 212° F. for the higher rank coals. Nitrogen was used to prevent oxidation before the starting temperature was reached. After the system reached equilibrium, oxygen was admitted, and the rate of temperature rise was measured. Results showed that the rate of heating increased rapidly with decrease in coal rank. Samples of lignite tested had a heating rate approximately 50 times that of a Pennsylvania bituminous coal.

Storage of Dried Lignite

After processing, the temperature of dried lignite is always above normal ambient temperatures. Therefore it is necessary to cool the product before storing.

Because large amounts of dried lignite have not been produced, extensive studies of storage have not been possible. However, approximately 300 tons of lignite have been steam-dried at Grand Forks, N. Dak., for use in gasification experiments, and approximately 100 tons was used in storage experiments.3/

The first experiment consisted of placing carefully screened dried lignite (1/2- by 1-1/2-inch) in layers 18 to 24 inches thick, without compaction. During screening and handling, the temperature of the lignite was reduced to 120° F. Both temperature- and gas-sampling stations were established within the storage pile. Owing to space limitations, the slope of the pile was rather steep. However, the temperature of the lignite decreased continuously and soon reached air temperature. After several months, gas analyses showed no evidence of combustion.

In a second experiment, a conical storage pile of dried lignite was formed without removal of fines. No attempt was made to prevent size segregation, and the pile was not compacted. After several days, steaming was observed, and temperature measurements indicated that the storage pile was heating, making it necessary to remove the lignite to prevent combustion.

For the third test another conical pile was built with 20 tons of dried lignite, which had been stored for 1 year. Previous storage showed no evidence of heating. The dried lignite had been produced from 1/2- by 1-1/2-inch, sized, natural lignite and had not been screened before the original storage; therefore, it contained some undersized product. Handling during the formation of the new storage pile probably increased the amount of fines. About 1 month after repiling, evolution of moisture indicated that heating was taking place, and it was necessary to remove the lignite to prevent combustion. This experiment showed that, although the dried lignite had been stored for a long period and was partly oxidized, conventional safe storage practice would still be necessary to prevent spontaneous combustion.

In smaller scale experiments, 2 samples of Dakota Star lignite, each about 400 pounds, which had been steam-dried at 400 p.s.i.g., were placed in wire-mesh containers and put in outside storage. Sample 1 was screened to 3/4 by 1-1/2 inch, and sample 2 was screened to 1/4 by 1/2 inch. After 27 months in storage, the

3/ See footnote 2.

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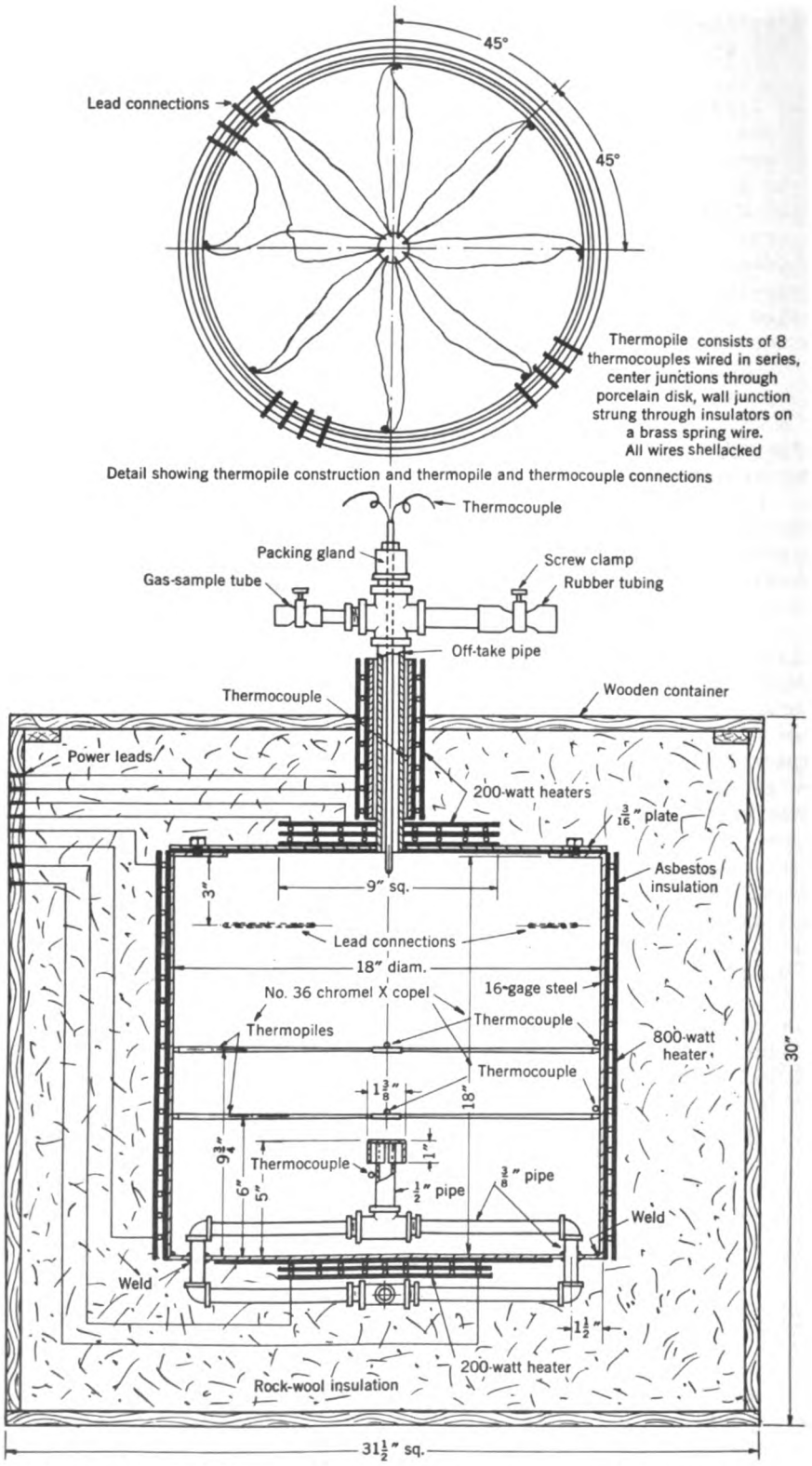

Figure 33. - Adiabatic calorimeter for spontaneous-heating tests on coal.

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samples were rescreened to determine size distribution and proximate and ultimate analyses were made. The data obtained are given in table 21.

TABLE 21. - Properties of steam-dried lignite before and after 27-month storage

	Before storage, as received	After storage, as received	Before storage, MAF	After storage, MAF
Sample 1:				
Proximate analysis:				
Moisture	12.4	15.8	-	-
Volatile matter	40.1	38.3	49.3	49.1
Fixed carbon	41.1	39.6	50.7	50.9
Ash	6.4	6.3	-	-
Ultimate analysis:				
Hydrogen	5.4	5.3	4.9	4.6
Carbon	58.2	55.5	71.6	71.1
Nitrogen	.7	.7	.9	.9
Oxygen	27.9	31.1	20.9	22.0
Sulfur	1.4	1.1	1.7	1.4
Ash	6.4	6.3	-	-
Heating value, b.t.u./lb	9,770	9,160	12,020	11,750
Sample 2:				
Proximate analysis:				
Moisture	10.0	16.3	-	-
Volatile matter	39.6	34.5	47.6	44.7
Fixed carbon	43.6	42.8	52.4	55.3
Ash	6.8	6.4	-	-
Ultimate analysis:				
Hydrogen	5.1	5.2	4.8	4.4
Carbon	58.3	55.5	70.0	71.8
Nitrogen	.9	.9	1.1	1.1
Oxygen	28.3	31.4	23.4	21.9
Sulfur	.6	.6	.7	.8
Ash	6.8	6.4	-	-
Heating value, b.t.u./lb	9,760	9,140	11,720	11,830

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TABLE 21 - Properties of steam-dried lignite before and after 27-month storage (Con.)

Screen size, inches	Original size 3/4 by 1-1/2 inch, percent retained	Original size 1/4 by 1/2 inch, percent retained
1.5	1.0	
1.05	10.0	
.742	25.6	
.525	25.1	7.3
.371	12.0	34.7
.263	6.2	34.7
.263	20.1	23.3
Above 3/4 inch	36.6	
Below 3/4 inch	63.4	
Above 1/4 inch		76.7
Below 1/4 inch		23.3

After exposure, both samples had about the same moisture content, indicating that, for the size range considered, equilibrium moisture content is independent of size distribution. The degree of degradation was greater for the large particles. Both samples showed more degradation than would occur under normal storage conditions. As carefully screened sizes were used, slacking was not restricted to the surface but extended into the interior of the storage container. Because of the unlimited supply of air, no heating occurred during storage. The change in heating value was small or negligible.

Storage at Industrial Sites

Periodic inspections have been made by the Bureau of Mines[4/] of storage piles of industrial users of lignite. The following summarizes storage procedures of three commercial users of lignite:

Otter Tail Power Co., Crookston, Minn.

The storage area at this plant measures 1,000 by 60 feet. Two types of storage are used, permanent storage stockpiled during the summer and temporary winter storage. During the summer the lignite is laid down in 1-foot layers to form a low, highly compacted storage pile. The maximum height of the pile is 7 feet. Approximately 7,000 tons is stored in this manner. During the winter an additional 1,600 tons of lignite is stored in a cone-shaped pile about 20 feet high. No special precautions are taken with this storage, as there is little danger of combustion, under winter conditions, in a storage pile of this size. However, this winter storage is consumed before hot weather arrives.

Minnkota Power Cooperative, Grand Forks, N. Dak.

Approximately 10,000 tons of lignite is stored in a 135- by 275-foot area, as shown in figure 34. Originally each layer of lignite (6 inches high) was packed by bulldozer, but this method did not produce uniform compaction, and hot spots resulted.

4/ See footnote 2.

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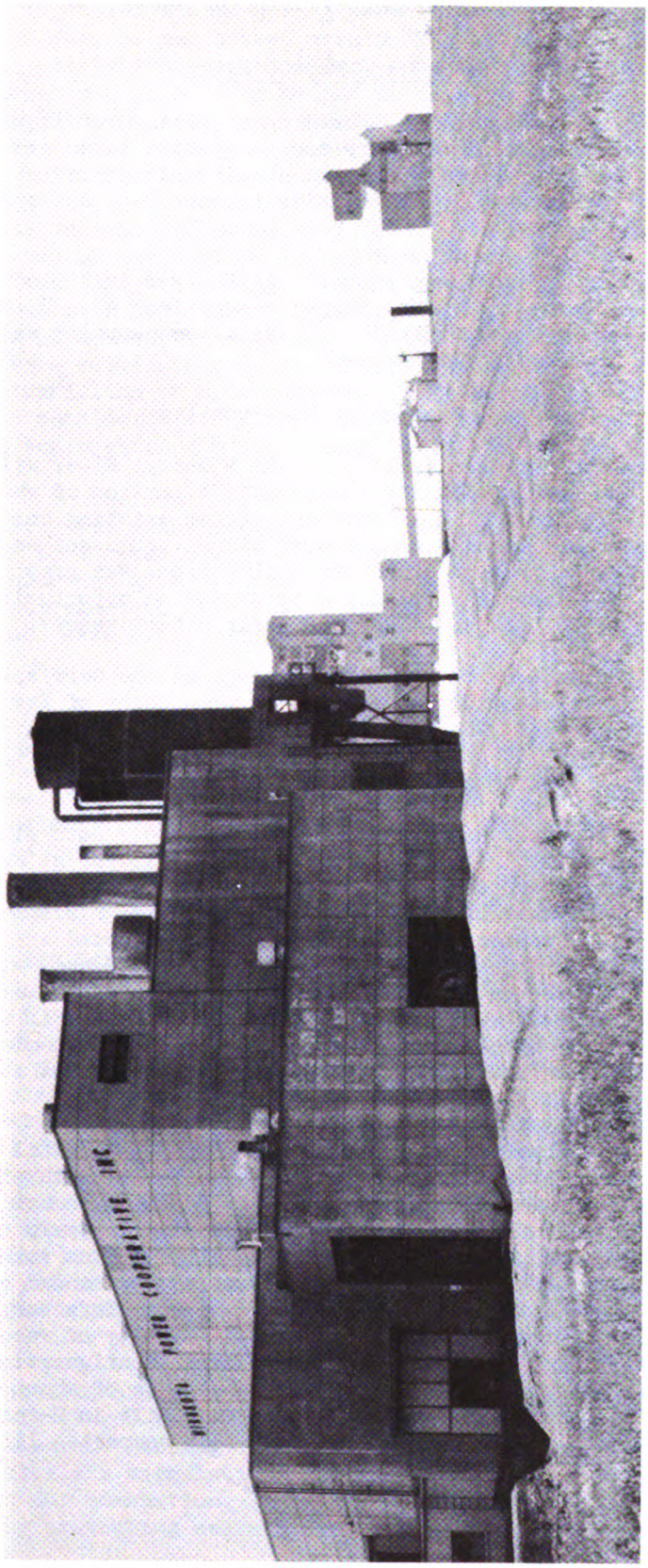

Figure 34. - Lignite storage at Minnkota Power Cooperative, Inc., Grand Forks, N. Dak.

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The use of a 2-ton roller in place of the bulldozer resulted in more uniform packing, and periodic inspections have shown no evidence of heating since this change in procedure.

American Crystal Sugar Co., East Grand Forks, Minn.

About 7,000 tons of lignite is stored in a rectangular storage pile 8 feet high. The 1-foot layers of lignite are compacted with 3-ton and 10-ton rollers. Localized heating occurs from time to time but is not considered a serious problem, as the period of storage usually is relatively short, and hot spots are easily removed.

The lignite used by all these concerns is 2- by 0-inch (industrial). Total annual consumption at the individual plants ranges from 40,000 tons to 100,000 tons. The storage piles are small in relation to annual consumption and are used only as insurance against transportation delays.

Storage at Garrison Dam

Excavation at the Garrison damsite on the Missouri River will expose an estimated 4 to 6 million tons of lignite, the greatest portion of which cannot be incorporated into the earth-fill construction. Under existing conditions, disposal of this large tonnage of lignite on the open market could not be considered; consequently, stockpiling, in hope of future utilization, was proposed as a solution. Such long-term, large-tonnage stockpiling presented an opportunity for employing different storage techniques and observing their effectiveness.

Technical assistance on the storage problems at the Garrison Dam was furnished by the Bureau of Mines upon the request of the Army Corps of Engineers. A summary of the investigations from 1948 to date is contained in a recent report by R. R. Allen and V. F. Parry (2). During the period covered by this report, five stockpiles were put down by various methods.

Piles 1 and 2 were put down in the spring of 1948. Both piles were shaped like the frustum of a pyramid. Pile 1 had gently sloping sides, at an angle of about 14°. Pile 2 had relatively steep sidewalls, sloping about 34°, and the sides of pile 2 were covered with a blanket of earth 11 feet thick. The finished piles were 15.5 and 28 feet in height, respectively. Pile 1 was constructed in 3-foot lifts. The 3- and 6-foot lifts and the surface were compacted by 2 passes with a D-8 crawler tractor. Two-foot lifts, each compacted in a similar manner, were employed in raising pile 2. Approximately 10,600 tons of lignite was stored in pile 1 and 13,150 tons in pile 2. The lignite placed in storage had been strip-mined, and the pieces as mined ranged in size from fines to large lumps, 6 to 8 feet across in the largest dimension. These latter were crushed in the compacting.

These piles were observed at intervals from June 1948 until 1950, when they were leveled to form a base for the extension of pile 3. Both piles were considered to be in good condition at all times during this period. No hot spots were noted, and gas analyses indicated that the piles had become relatively stabilized. The exposed lignite had slacked, and the resultant small particles formed a satisfactory surface seal. The earth walls on pile 2 had settled and eroded considerably. Storage in piles of this type was considered to be unsatisfactory, because of the maintenance required for the sidewalls and the difficulty of recovering uncontaminated lignite. A third pile having the same general configuration as pile 1 was constructed in two adjacent sections, with a total base of about 1,950 by 230 feet. The first section, a segment of some 230 feet, was built in 2-foot uncompacted lifts; the second section was constructed in 1-foot compacted lifts.

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The lifts in the first section of pile 3 were built up from as-mined lignite dumped on the pile from Euclids and spread evenly by bulldozer. Spreading without compaction resulted in considerable segregation, with concentration of larger lumps along the western side of the pile. The second section was begun when the height of the first was about 10 feet. Placing the lignite in 1-foot lifts, followed by compaction, resulted in little segregation, as the large lumps were crushed, and the size range of the entire lift was relatively uniform.

Segregation in the uncompacted portion of pile 3 was accentuated by the partial crushing caused by travel of the Euclids in the dumping area. This segregation, coupled with the fact that the prevailing winds in the area are from the west, caused concern that the northwestern portion of the pile could be a focal point for spontaneous heating. Some 10 months later the uncompacted portion of pile 3 ignited. At least three fires were eliminated during the following months, necessitating removal, cooling, and backfilling of a considerable portion of that pile. Repiling the cooled lignite was considered safer practice than using fresh lignite. Thus, the value of avoiding segregation and compacting lifts was forcibly illustrated.

In adding segments to the southern end of pile 3, it was found that rolling the dumped and leveled lifts with a sheepsfoot roller resulted in better compacting and less segregation. Six to 10 passes with the sheepsfoot roller effectively crushed and compacted the lignite and gave a relatively smooth surface for the Euclids. This modification in storage technique was so satisfactory, both from the viewpoint of better compaction and ease of stockpiling, that it was adopted as standard operating procedure.

Piles 4 and 5 were begun in the fall of 1949. Additions to these piles and pile 3 are now being made as required by excavation operations. The procedure used to construct these piles is as follows: The as-mined lignite is dumped from the Euclids, leveled to the correct height for approximately a 12-inch lift by bulldozer, and compacted by sheepsfoot roller. Usually the entire pile segment is compacted before the next lift is begun. Use of a chopper roller in conjunction with the sheepsfoot has been found to be advantageous in securing additional compaction. Formation of a storage pile employing these techniques is illustrated in figure 35.

Stockpiles are being formed under careful supervision and are considered to be in excellent condition, with only a remote possibility of spontaneous ignition. The respective location and relative size of the five piles in 1950 is shown in figure 36. As of July 15, 1951, some 817,000 cubic yards, or about 885,000 tons of lignite, had been excavated and placed in storage. Some lignite has been removed from storage and used in the local steam plant. The total amount of lignite stored is less than was originally estimated, because of inclusion of a higher percentage of lignite in the earth fill for the dam.

The heavy crushing and compacting equipment - sheepsfoot and chopper rollers - used to construct the storage piles at Garrison Dam are required primarily because of the large size of the lignite as received for storage direct from the mining operation, which includes pieces several feet long. In storing 2- by 0-inch industrial fuel, smooth rollers and bulldozers have been used to compact storage piles adequately.

Stockpiling at Garrison and by industrial users has shown that large tonnages of lignite may be safely stored for extended periods if proper techniques are employed. To avoid spontaneous heating in large open storage, the most important consideration is to minimize air circulation through the pile to prevent continuous introduction of oxygen for combustion. This air circulation may be restricted by thorough compaction, by preventing segregation, and by having a smooth pile surface.

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Figure 35. - Formation of storage pile at Garrison damsite, using recommended techniques: Sheepsfoot roller and chopper (foreground), bulldozers (center and right background), Euclids (left background).

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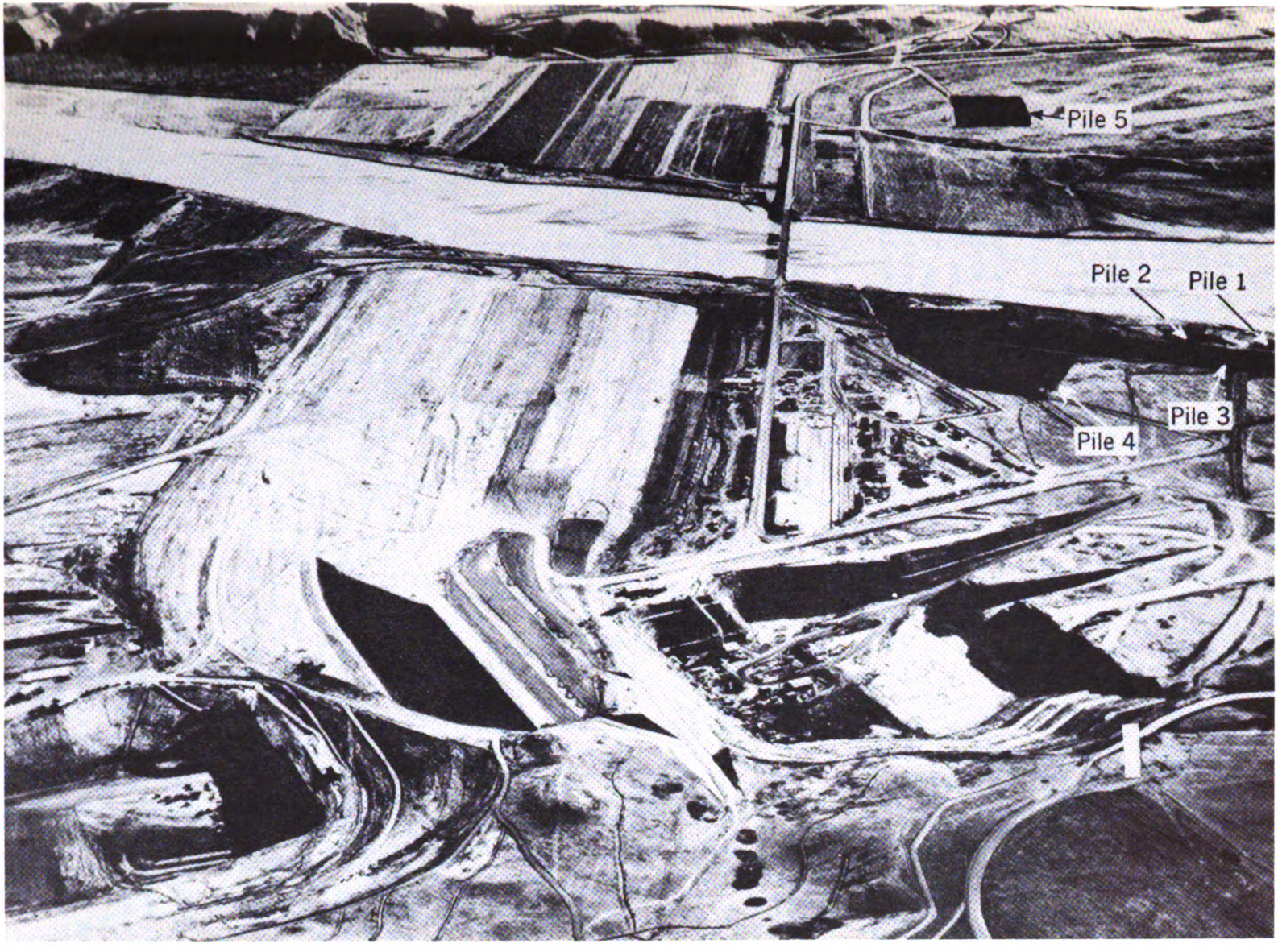

Figure 36. - Location and relative size of storage piles at Garrison damsite.
(Corps of Engineers' photograph)

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Transportation

Railroad Transportation

Most of the lignite mined in North Dakota and not used at the minesite is transported by rail. Lignite for power plants and other relatively large consumers is shipped in standard open gondola cars of 50 to 70 tons capacity. Large lump fuel for the domestic market usually is shipped in boxcars. Even for the fine industrial sizes, and without any particular precautions in loading, no difficulty from spontaneous ignition is encountered during the short periods - 6 to 8 days maximum - that the lignite is normally in transit. During the winter, freezing and agglomeration in cars may cause unloading problems. In present practice, oil treatment is commonly used to alleviate this difficulty.

The largest population centers and greatest demand for fuel are in the eastern part of the lignite-consuming region. Much of the production is therefore shipped 200 miles or more to these eastern consuming centers. Table 22 shows freight rates and distances from some of the larger mines to Grand Forks and Fargo, N. Dak. Rates for shipping lignite to Minneapolis, Minn., are also given for comparison. At present, lignite is not shipped to Minneapolis because the transportation cost is too high for lignite to be competitive in that area.

Separate rates have been established for shipment within North Dakota for industrial lignite and for domestic lump, with rates for domestic sizes at a slightly higher level. Rates per ton for interstate shipment are the same for all sizes.

TABLE 22. - Freight rates for rail shipment of industrial lignite[1/]

Station	To Grand Forks		To Fargo		To Minneapolis, Minn.	
	Freight rate, $/ton	Distance, miles	Freight rate, $/ton	Distance, miles	Freight rate, $/ton	Distance, miles
Kincaid.....	2.22	293	2.35	316	3.48	552
Noonan.....	2.35	305	2.35	326	3.48	563
Beulah.....	2.71	351	2.22	273	3.35	514
Zap.....	2.71	358	2.22	281	3.35	521
Dickinson.....	2.71	377	2.22	300	3.48	540
Hazen.....	2.58	343	2.22	265	3.35	506

1/ Include ex parte 175-B increase.

The approximate extent of the present consuming area for industrial lignite is shown in figure 37. This area covers North Dakota and extends for some distance into Minnesota and South Dakota. To the north and west of the lignite-producing area no markets now exist, because for present needs supplies of coal are available locally in those areas that can also be mined at low cost. To the east and southeast the consuming area extends to the limit where fuel cost of rail-transported lignite is approximately the same as the cost of coal delivered from the Great Lakes ports, or barged up the Mississippi River from the coal fields of Illinois, Missouri, and Kentucky.

Effect of Drying on Transportation Costs

The consuming area for lignite could perhaps be extended and savings in transportation costs made by developing low-cost methods for moisture removal. Confirmation of a net transportation cost advantage for dried fuel depends on freight rates established for this upgraded higher heating-value product, relative to existing rates for lignite, as mined. Present rates per ton for shipment of higher rank

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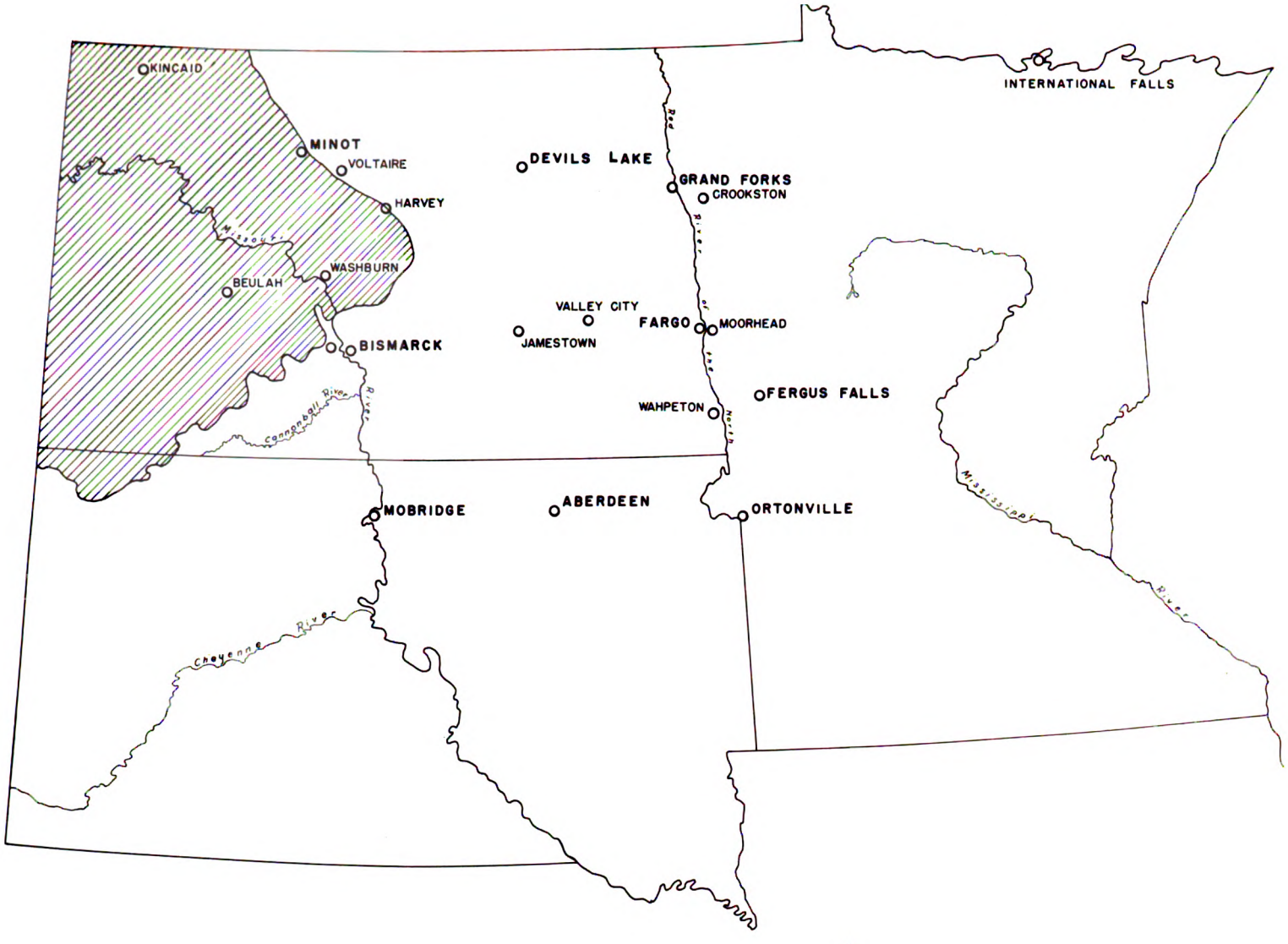

Figure 37. - Location of lignite-burning power plants.

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coals exceed rates for lignite, as mined. Within North Dakota, however, rates per ton for lignite-char briquets, with nearly twice the heating value per unit weight of lignite, as mined, have been established at the same level as rates for as-mined lignite.

Steam-dried lump lignite can be stored and shipped in open cars and containers. Equilibrium moisture content is about 15 percent, corresponding to a reduction to 3/4 of the weight as mined, with full retention of heating value. Based on estimated minimum drying cost of 50 cents per ton of as-mined lignite,5/ this process would be marginal for use in shipment to consuming centers within North Dakota, if existing freight rates for as-mined lignite (table 22) were maintained for dried lignite. There would be a clear advantage for steam drying only for interstate shipment, at rates equal to or not greatly in excess of existing rates for as-mined lignite.

By fluidized drying, lignite can readily be dried to low moisture content (4 percent or less) at minimum drying cost. However, the fine-particle dried product is highly subject to ignition and can be stored or shipped only in closed containers. Thus there is little reason to believe that this process can be used to reduce cost of conventional transportation by rail.

Surface coating and partial agglomeration of direct-heat-dried lignite by using small quantities of binding agent have been considered as a method of providing a stable product suitable for conventional shipment (11).

Water-Route Transportation

Water-borne transportation is not available in the lignite area, except along the Missouri River. Most of this river will be navigable when the present system of dams is completed, and some plans have been made for local barge shipments. At present, no provision has been made for bypassing dams by river traffic, which limits the area for shipment. In any event, however, no large markets are attainable along the Missouri River, to north or south, within reasonable distances.

Long-Distance Power Transmission; Coal Pipeline

There are two principal areas some distance from the North Dakota lignite deposits, which could provide large-scale markets for lignite or lignite-generated power if low-cost transportation were available. These are the Minneapolis-St. Paul industrial area, and the northern Minnesota iron-range country, where very large amounts of electric power will be required to process low-grade taconite deposits.

Existing power capacity in the Minneapolis-St. Paul area is approximately 500,000 kw. In the taconite area an estimated minimum of 600,000 kw. will be required in the near future, based on present plans for development (8). Each of these areas is about 450 miles from the lignite deposits.

Two principal methods can be considered that are of potential value for making fuel or power available to large concentrated markets at low cost over comparable distances. These are coal transportation by pipeline and long-distance transmission of minesite-generated power at high voltages.

5/ See footnote 2.

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Comparative investment and operating costs for each of these two methods, based on data now available, are presented in figures 38 and 39. Capacities or equivalent capacities of 500,000 to 2,000,000 kw. are considered. Relationship between transmission of fuel and of power is based on 11,400 B.t.u. per kw.-hr. and 7,000 B.t.u. per lb. of lignite. Data on coal-pipeline costs are taken from a recent study by the Bureau of Mines (5). Power-transmission costs, for 500,000 volt transmission, are derived from cost data prepared by the Bureau of Reclamation (4). The Bureau of Mines coal-pipeline study is based on water-slurry transporation at 35 percent solids. As a conservative assumption, slurry transportation of lignite at 35 percent by weight of lignite, as mined, has been assumed in preparing figures 38 and 39. Coal-pipeline costs are based on known costs for oil pipelines, with added allowance for pumping-station maintenance, based on available experience in slurry pumping of coal and other solids. Pipeline depreciation is taken at 9 percent per year, plus an allowance for maintenance supplies and materials of 1 percent for line and 3 percent for pumping stations. Costs as presented include only pipeline transmission and do not include dewatering facilities. The Bureau of Reclamation power-transmission costs, as prepared, are based on 500,000-volt transmission over a 660-mile line. In calculating cost of 450-mile transmission (fig. 39), it has been assumed that the total cost, including substations and auxiliary equipment, is approximately proportional to line length. Five hundred thousand-volt transmission has not yet been achieved in practice, and costs can be considered to represent minimum power-transmission costs.

Cost data in figure 39 show that pipeline transportation or long-distance power transmission will presumably require larger markets than are likely to be available in the two consuming areas under consideration in the immediate future, although longer term possibilities may exist.

Coal transporation both by pipeline and long-distance power transmission requires large-scale consumption at a fixed high level to be economically justified. Relatively constant demand level, both daily and seasonal, should be achievable in a unified development like taconite processing. In providing for the power requirements of the Minneapolis-St. Paul area, long-distance transmission of fuel or power could be used only to supply the firm base requirements.

Pipeline transporation has somewhat greater flexibility and adaptability than power transmission, since the product can be stored, if necessary, at the point of delivery and since fuel requirements other than power generation can be provided for. Very large requirements, specifically for fuel, may eventually be developed in the iron-range country, in connection with the processing of nonmagnetic taconites, or for other ore-reduction processes, and pipeline transporation could make lignite the lowest-cost coal available to meet these requirements. In general, pipeline transporation could also be used to lower the cost of transporation to the consuming center of competitive coals. However, for the two markets considered, lignite would be competing directly with coals that already have the advantage of low-cost water-borne transportation.

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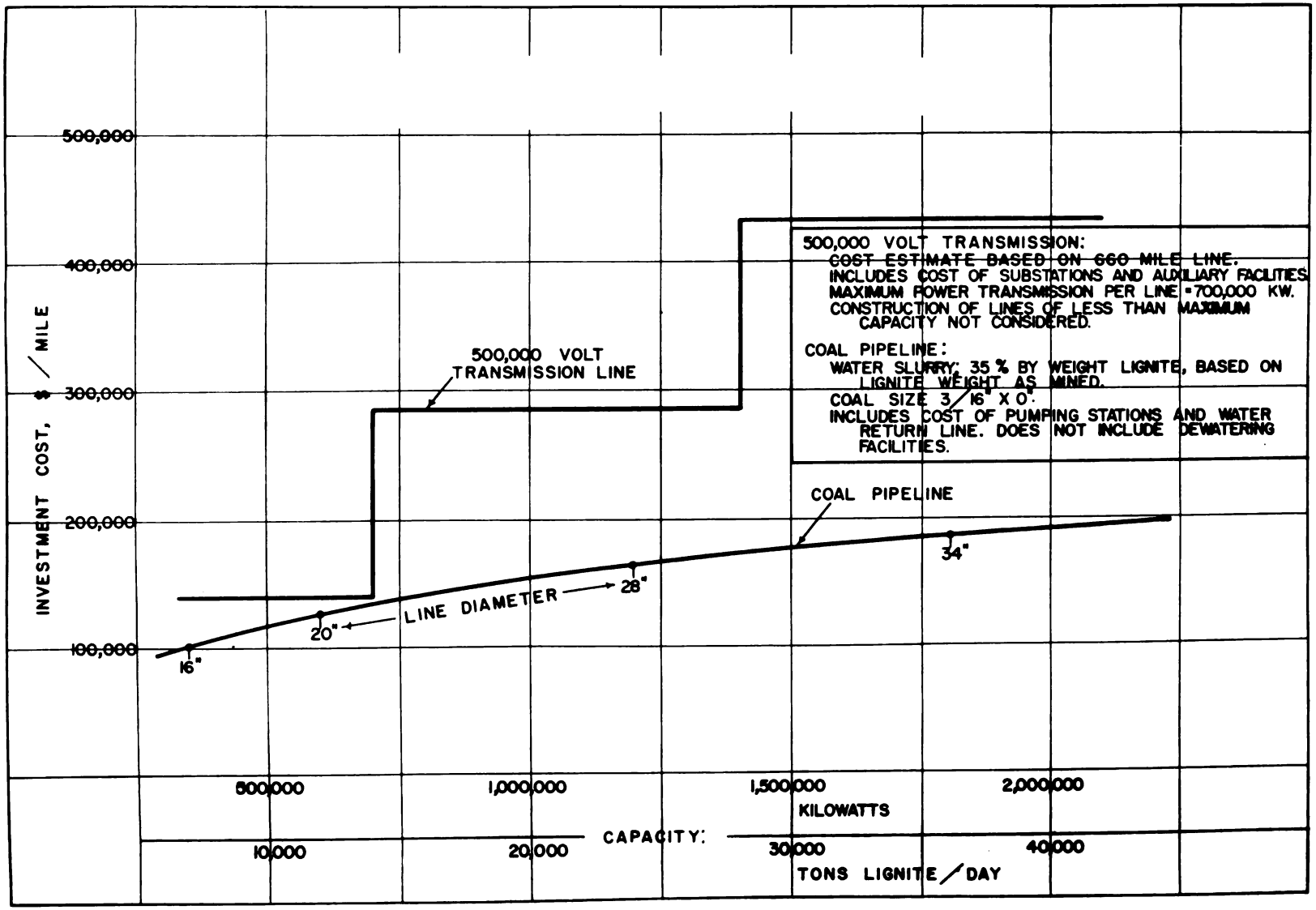

Figure 38. - Investment cost, long-distance power transmission vs. coal pipeline.

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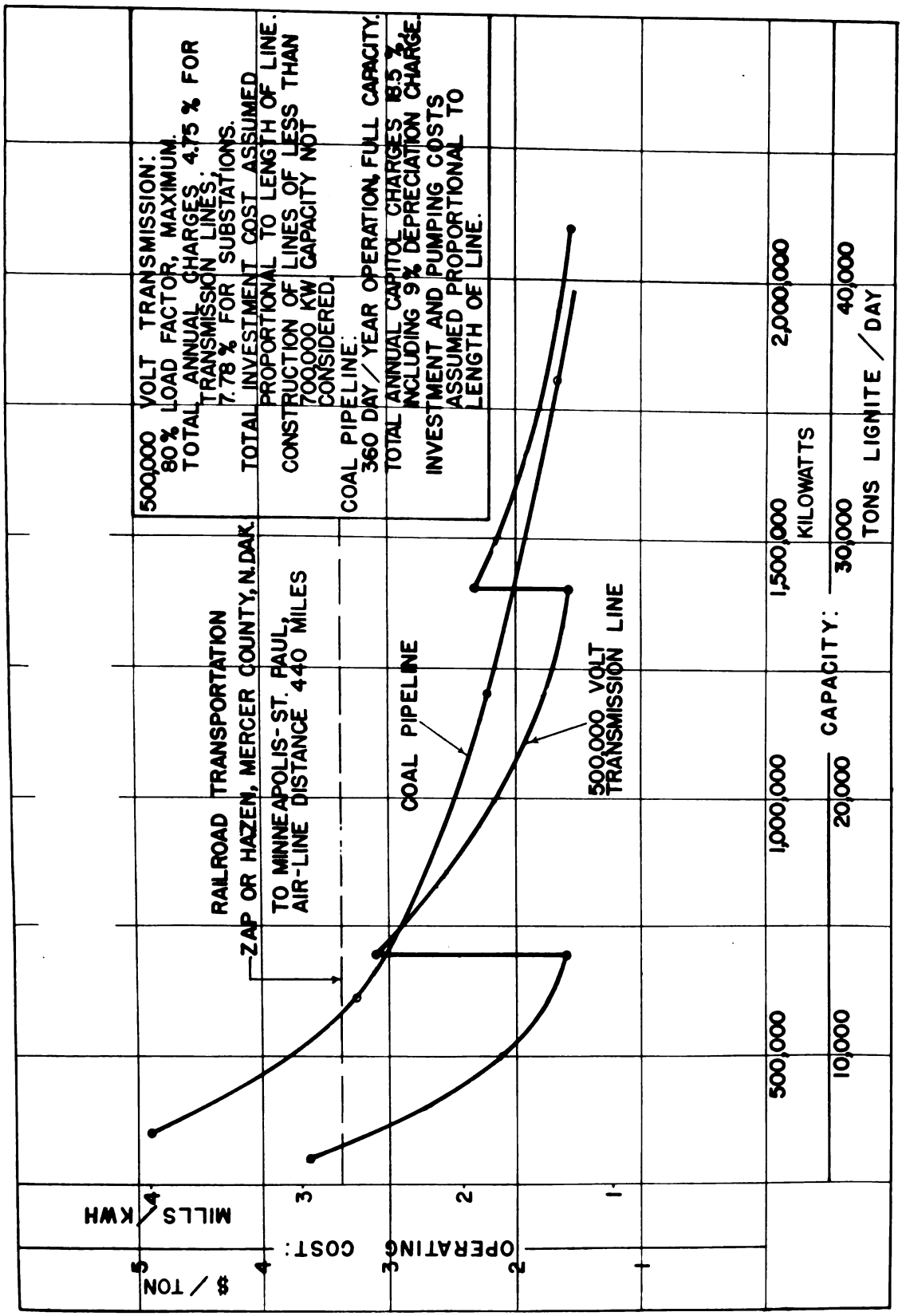

Figure 39. - Operating cost, power transmission vs. coal pipeline, 450 miles.

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APPENDIX. - STATISTICS AND COSTS OF LIGNITE IN NORTH DAKOTA[1/]

Although the trend in bituminous-coal and lignite production for the country as a whole has been one of significant decline in postwar years, despite continued increase in the overall demand for energy, production of lignite in North Dakota has been unique in that it has increased so steadily as to have approximately doubled in the past 25 years, as indicated in table 23.

Of the various factors responsible for this converse trend, probably the most important is the heavy and continually increasing proportion of output produced by stripping operations, the steady growth of thermal power production to meet the increasing demands for electric power in the region, and a lesser availability of some of the other sources of energy as compared to other areas.

Table 23, which shows the historical pattern of lignite production and related factors in North Dakota from 1926 through 1952, and table 24, which shows production separately for underground and stripping operations for 1940 through 1952, emphasize the proportionately heavy increase in strip production. Although total production has doubled in the last 25 years, the number of employees has been cut in half and the number of mines has been reduced by two-thirds. On the other hand, production per man-day has increased from 6.56 tons in 1926 to 23.56 tons in 1952.

As shown in table 24, the increased acceleration that began in 1940, when output per man-day was 8.57 tons, has continued through 1952. During this period underground production dropped from 812,844 tons to 183,343 tons, or from 37 percent to only 7 percent of total production. The output from stripping operations increased from 1,405,590 tons to 2,800,409, or from 63 to 93 percent of total production. The average output per man-day in underground mines in 1952 was 7.40 tons, and at stripping operations was 27.48 tons, for the overall average of 23.56 tons.

During the various periods shown in the respective tables that are part of this report, the average value of North Dakota lignite f.o.b. mines has increased steadily, having more than doubled between 1940 and 1952, from $1.17 to $2.37 per ton.

The trends in production and value vary widely between the respective counties; and analysis of such a breakdown, in coordination with other pertinent factors may prove helpful in fully appraising the potentialities for North Dakota lignite. Table 25 has been prepared to show production, value per ton, and tons per man-day for each of the respective counties for which data are available for 1926 through 1952.

Of particular interest are Mercer, Ward, Burke, and Divide Counties, where output per man-day has averaged approximately 22, 26, 31 and 38 tons, respectively, for the larger operations. Also worthy of note are the changes in Bowman County during the past few years, where output per man-day was over 39 tons in 1952 and value per ton f.o.b. mines was $1.64.

1/ Costs of production are not available; as used herein cost refers to value of the lignite f.o.b. mines, before the addition of transportation charges, but with the operator's profit.

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TABLE 23.—Production and value of lignite in North Dakota, 1926-52 1/

Year	Production (in 000's)				Value 3/		Number of employees				Average No. of		Ave. No. of working days
	Rail shipments	Sales by truck or wagon	Other disposition 2/	Total	Total $(000's)	Ave. per ton	Under ground	In strip pits	Other	Total	Tons per man day	Mines	
1926	1,066	268	36	1,370	2,378	$1.74	712	430	146	1,288	6.56	150	162
1927	1,213	290	25	1,528	2,604	1.70	744	466	131	1,341	6.78	153	168
1928	1,320	312	18	1,650	2,780	1.68	803	399	133	1,335	7.00	150	177
1929	1,443	381	38	1,862	3,157	1.70	772	483	166	1,421	6.84	143	192
1930	1,336	345	19	1,700	2,768	1.63	638	496	124	1,258	7.50	156	180
1931	1,147	355	17	1,519	2,155	1.42	772	275	253	1,300	7.04	169	166
1932	1,345	337	58	1,740	2,200	1.26	696	304	311	1,311	7.12	146	186
1933	1,349	312	121	1,782	2,248	1.26	645	364	292	1,301	7.93	138	173
1934	1,282	347	125	1,754	2,363	1.35	728	437	353	1,518	6.65	157	174
1935	1,436	437	82	1,956	2,395	1.22	668	424	273	1,365	7.61	161	188
1936	1,619	450	146	2,215	2,534	1.14	662	408	338	1,408	8.20	169	192
1937	1,577	471	203	2,251	2,639	1.17	689	w/	w/	1,475	8.41	180	181
1938	w/	w/	w/	2,050	2,380	1.16	w/	w/	w/	1,370	8.62	156	174
1939	1,522	404	146	2,072	2,425	1.18	560	305	349	1,214	9.04	102	179
1940	1,567	508	143	2,218	2,587	1.17	654	371	352	1,377	8.83	121	182
1941	1,709	412	188	2,309	2,937	1.27	562	444	269	1,275	10.23	113	177
1942	1,882	525	130	2,537	3,554	1.40	491	386	307	1,184	10.46	100	205
1943	1,899	517	84	2,500	3,752	1.50	405	324	273	1,002	11.17	106	223
1944	1,865	411	90	2,366	3,554	1.49	292	254	280	826	13.48	84	213
1945	2,023	430	69	2,522	3,924	1.56	227	282	248	757	14.73	53	226
1946	2,097	374	84	2,555	4,302	1.68	156	255	263	674	15.73	47	241
1947	2,228	458	74	2,760	5,312	1.92	154	279	247	680	15.89	46	255
1948	2,407	473	81	2,961	6,729	2.27	135	239	246	620	18.35	41	260
1949	2,366	509	92	2,967	7,004	2.36	133	260	244	637	19.57	43	238
1950	2,526	576	159	3,261	7,758	2.38	119	276	229	624	22.32	44	234
1951	2,514	446	264	3,224	7,770	2.41	110	301	265	676	20.06	54	238
1952	2,402	366	216	2,984	7,072	2.37	85	300	243	628	23.56	49	202

1/ Excludes mines producing less than 1,000 tons annually.
2/ Coal used by employees, taken by locomotives at tipple, used at mine for power and heat, used in briquets, etc.
3/ F.o.b. mines.
w/ Not available.

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TABLE 24.—Production of lignite in North Dakota by underground and strip mining methods, 1940-52
(in net tons)

Year	Underground 1/		Strip mining				Total		
	Tons	Percent of total	Tons	Percent of total	Average value per ton	Average tons per man day	Tons	Average value per ton	Average tons per man day
1940	812,844	37	1,405,590	63	$1.14	13.28	2,218,434	$1.17	8.83
1941	781,744	34	1,527,144	66	1.24	16.27	2,308,888	1.27	10.23
1942	821,527	32	1,715,489	68	1.37	15.21	2,537,016	1.40	10.46
1943	750,480	31	1,749,722	69	1.46	16.21	2,500,202	1.50	11.17
1944	709,625	30	1,656,467	70	1.50	17.59	2,366,092	1.49	13.48
1945	662,645	27	1,859,674	73	1.53	19.06	2,522,319	1.56	14.73
1946	427,106	17	2,127,576	83	1.60	19.76	2,554,682	1.68	15.73
1947	472,190	17	2,287,672	83	1.93	19.30	2,759,862	1.92	15.89
1948	484,831	16	2,476,158	84	2.30	22.08	2,960,989	2.27	18.35
1949	470,347	16	2,496,913	84	2.40	23.68	2,967,260	2.36	19.57
1950	432,917	13	2,828,056	87	2.40	27.45	3,260,973	2.38	22.32
1951	250,901	8	2,973,126	92	2.42	23.30	3,224,027	2.41	20.06
1952	183,343	7	2,800,409	93	2.36	27.48	2,983,752	2.37	23.56

1/ Average values per ton and per day not available for all years for underground production.

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TABLE 25. - North Dakota lignite production, average value per ton f.o.b. mines, and average tons produced per man-day, by counties, 1926-52 (tons are expressed in net tons of 2,000 pounds)

Year and item	COUNTY																				
	Adams	Billings	Bowman	Burke	Burleigh	Divide	Dunn	Golden Valley	Grant	Hettinger	McKenzie	McLean	Mercer	Morton	Mountrail	Oliver	Slope	Stark	Ward	Williams	Total
1926 Production	59,803	(1)	59,383	336,230	184,700	25,700	4,454	5/4,845	14,695	22,157	-	94,214	351,657	43,109	5,534	(1)	-	90,935	46,145	56,749	1,379,244
Average value per ton	$1.89	(1)	1.25	1.89	1.77	2.10	2.25	2/1.86	1.84	1.81	-	2.04	1.36	1.65	2.72	(1)	-	1.73	2.19	2.13	1.74
Average tons per man-day*	6.34	(1)	7.94	12.08	7.18	2.77	3.06	2/4.33	3.85	4.03	-	4.69	10.15	5.06	2.16	(1)	-	3.31	2.39	3.40	6.56
1927 Production	57,714	(1)	55,716	292,624	234,266	16,216	6,379	3/4,257	12,109	27,265	(1)	103,787	405,355	41,330	6,365	3,435	-	50,787	142,574	67,961	1,527,939
Average value per ton	$1.85	(1)	1.36	1.73	1.60	2.47	2.19	3/1.88	1.98	1.72	(1)	2.08	1.45	1.74	2.59	1.46	-	1.91	1.89	2.05	1.70
Average tons per man-day*	4.95	(1)	6.04	19.74	6.97	2.48	3.63	3/3.17	3.26	3.09	(1)	5.60	10.01	3.38	2.34	3.67	-	2.80	6.61	3.58	6.78
1928 Production	50,382	(1)	48,416	293,969	229,490	17,784	3,338	3/5,010	18,835	21,239	(1)	81,588	448,188	43,759	4,372	4,191	-	54,099	242,483	62,977	1,649,930
Average value per ton	$1.81	(1)	1.51	1.71	1.53	2.36	2.40	3/2.00	2.12	1.79	(1)	2.05	1.50	1.83	2.74	1.45	-	1.43	1.81	1.95	1.68
Average tons per man-day*	4.94	(1)	5.00	15.70	6.47	2.55	2.50	3/2.40	3.74	3.14	(1)	4.82	9.67	3.45	1.88	2.81	-	3.56	9.47	3.97	7.00
1929 Production	50,631	(1)	39,084	4/329,650	228,294	(5)	4,268	5/5,339	21,308	23,326	2,941	104,779	494,803	42,195	4,246	3,309	-	107,978	333,559	66,367	1,862,130
Average value per ton	$1.86	(1)	1.71	4/1.77	1.58	(5)	2.11	5/2.06	1.97	1.67	1.70	2.02	1.57	1.83	2.58	1.51	-	1.65	1.61	1.94	1.70
Average tons per man-day*	5.26	(1)	4.58	4/15.42	6.42	(5)	2.18	5/4.20	2.82	3.54	2.56	5.03	7.79	3.37	1.78	2.73	-	3.46	11.34	3.31	6.84
1930 Production	52,913	-	26,681	262,732	195,350	19,597	3,524	1/5,219	24,643	19,958	(1)	109,139	436,720	37,601	9,370	3,300	-	60,956	367,244	61,826	1,700,157
Average value per ton	$1.50	-	1.72	1.64	1.57	2.25	1.99	1/1.92	1.74	1.75	(1)	1.82	1.58	1.86	2.40	1.52	-	1.57	1.53	1.91	1.63
Average tons per man-day*	5.70	-	4.03	19.34	8.95	2.45	2.31	1/3.33	3.60	2.92	(1)	5.06	8.63	3.09	2.25	3.00	-	4.82	10.83	3.61	7.59
1931 Production	55,201	-	20,164	184,262	195,993	75,700	1,368	(8)	25,504	18,321	(8)	99,215	415,669	26,628	8,313	2/4,700	-	36,728	325,339	26,232	1,519,307
Average value per ton	$1.83	-	1.39	1.36	1.38	1.47	1.44	(8)	1.69	1.47	(8)	1.61	1.36	1.77	1.80	2/1.49	-	1.14	1.36	1.72	1.42
Average tons per man-day*	3.78	-	2.47	26.01	13.41	11.18	1.93	(8)	2.68	2.71	(8)	4.34	7.08	3.42	1.75	2/6.06	-	4.85	9.40	2.76	7.04
1932 Production	53,529	-	10,739	193,971	213,523	156,383	-	(8)	33,331	18,155	(8)	107,041	509,223	24,077	5,122	2/4,337	-	42,692	337,906	29,662	1,739,698
Average value per ton	$1.63	-	1.40	1.12	1.18	1.31	-	(8)	1.53	1.38	(8)	1.43	1.23	1.68	1.96	2/1.15	-	1.38	1.02	1.52	1.26
Average tons per man-day*	5.85	-	3.08	14.46	11.11	13.39	-	(8)	3.49	2.54	(8)	4.73	8.11	3.87	2.38	2/2.38	-	3.31	6.79	2.62	7.12
1933 Production	45,965	-	19,583	187,519	235,438	202,283	10/6,238	(11)	23,724	14,942	-	115,728	469,161	24,956	4,548	(11)	-	55,744	351,119	30,796	1,782,272
Average value per ton	$1.63	-	1.28	1.25	1.29	1.22	10/1.28	(11)	1.52	1.35	-	1.42	1.20	1.49	1.48	(11)	-	1.15	1.02	1.49	1.26
Average tons per man-day*	4.49	-	3.49	10.92	12.34	15.20	10/2.67	(11)	2.97	2.90	-	5.15	8.47	5.02	2.49	(11)	-	5.24	9.24	3.55	7.23
1934 Production	25,089	-	17,100	158,387	224,612	179,192	12/4,424	(11)	27,504	12,117	-	125,010	454,801	30,631	6,437	3,200	-	60,739	387,003	34,437	1,753,838
Average value per ton	$1.32	-	1.29	1.43	1.39	1.36	12/1.13	(11)	1.49	1.16	-	1.33	1.33	1.41	1.40	1.25	-	1.15	1.31	1.60	1.35
Average tons per man-day*	4.51	-	3.61	7.36	8.61	17.25	12/3.07	(11)	5.08	3.59	-	4.60	7.20	5.24	2.48	2.78	-	4.27	6.24	3.42	6.65
1935 Production	22,008	-	19,032	209,780	232,053	206,200	(8)	(8)	24,250	17,743	(8)	119,444	524,473	27,696	8,746	13/11,400	-	90,016	411,543	31,436	1,955,510
Average value per ton	$1.27	-	1.11	1.20	1.24	1.28	(8)	(8)	1.24	1.30	(8)	1.36	1.21	1.44	1.37	13/1.05	-	1.13	1.15	1.75	1.22
Average tons per man-day*	3.52	-	4.21	7.60	9.15	14.23	(8)	(8)	4.82	3.12	(8)	5.07	9.17	5.78	2.37	13/3.46	-	4.38	8.39	3.15	7.61
1936 Production	21,261	(14)	12,982	253,351	250,684	232,616	8,541	4,080	25,120	15,961	15/6,993	153,911	572,658	32,020	9,359	6,340	-	88,585	481,305	38,719	2,215,339
Average value per ton	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	-	n.a.	n.a.	n.a.	$1.14
Average tons per man-day*	$2.94	(14)	6.24	9.86	11.36	15.13	4.54	2.98	5.14	2.92	15/4.03	6.26	8.78	5.42	2.32	4.47	-	6.07	8.93	3.13	8.20
1937 Production	34,161	(16)	17/10,694	244,022	253,900	209,804	7,380	2,499	29,437	16,991	4,404	151,958	583,094	31,217	12,428	8,916	(16)	129,350	479,721	44,819	2,250,537
Average value per ton	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	$1.17
Average tons per man-day*	$3.16	(16)	17/5.05	13.48	11.41	13.46	3.73	2.73	5.30	2.94	2.81	6.14	9.07	4.38	2.32	5.50	(16)	6.32	9.27	3.96	8.41
1938 Production	41,602	(1)	5,704	238,424	227,433	166,391	3,353	18/4,621	23,035	17,515	5,549	128,799	545,380	28,374	12,996	7,647	(1)	90,932	453,675	48,592	2,250,069
Average value per ton	$1.34	(1)	1.40	1.13	1.20	1.24	1.19	18/1.30	1.26	1.20	1.44	1.44	1.05	1.20	1.39	0.92	(1)	1.10	1.14	1.34	1.16
Average tons per man-day*	3.58	(1)	3.77	17.26	11.97	14.52	4.47	18/1.94	6.23	3.64	2.37	5.27	5.98	5.09	2.38	4.47	(1)	6.24	8.96	4.37	8.42
1939 Production	45,975	(11)	7,554	251,627	229,592	169,998	12/8,231	6,000	23,832	12,779	5,414	146,120	583,000	24,069	9,350	6,158	(11)	92,906	472,997	38,834	2,131,262
Average value per ton	$1.11	(11)	1.32	1.14	1.17	1.16	12/1.53	1.17	1.26	1.17	1.66	1.27	1.07	1.24	1.49	0.97	(11)	1.02	1.13	1.31	1.14
Average tons per man-day*	4.11	(11)	3.24	14.21	12.99	13.47	12/4.25	2.97	4.53	3.77	2.55	6.07	9.84	4.99	2.81	3.51	(11)	6.19	8.52	4.17	8.57
1940 Production	48,434	(16)	20/12,163	260,480	255,885	154,073	(16)	6,825	24,791	14,800	5,690	142,123	621,005	24,197	6,041	13,023	(16)	113,407	477,016	37,624	2,218,434
Average value per ton	$1.26	(16)	20/1.56	1.17	1.20	1.32	(16)	1.17	1.25	1.28	1.41	1.25	1.06	1.24	1.32	1.00	(16)	1.11	1.17	1.33	1.17
Average tons per man-day*	4.04	(16)	20/4.03	14.91	13.66	15.60	(16)	2.99	4.89	3.87	3.67	5.85	11.45	4.20	2.14	3.63	(16)	5.08	8.18	4.24	8.83
1941 Production	21/66,662	(22)	9,675	278,460	283,261	181,464	5,655	7,200	12,807	13,464	3,829	131,935	656,773	23,943	11,843	10,395	(23)	24/116,171	470,079	25,359	2,303,388
Average value per ton	21/$1.55	(22)	1.65	1.28	1.26	1.22	1.41	1.51	1.41	1.34	1.65	1.43	1.25	1.34	1.52	0.96	(23)	24/1.17	1.23	1.50	1.27
Average tons per man-day*	21/4.45	(22)	3.96	22.07	16.32	14.12	3.83	3.30	5.16	4.08	4.24	6.78	12.22	4.68	3.26	5.18	(23)	24/5.23	11.19	3.65	10.23
1942 Production	57,451	(16)	25/10,269	326,424	303,979	217,553	6,796	8,164	28,573	19,706	3,661	135,915	682,332	34,957	14,434	20/8,439	(8)	128,331	517,231	32,656	2,537,316
Average value per ton	$1.83	(16)	25/3.18	1.43	1.32	1.34	2.06	1.84	1.68	1.73	1.97	1.50	1.38	1.66	1.87	20/1.30	(8)	1.28	1.33	1.71	1.40
Average tons per man-day*	4.89	(16)	21/4.36	17.74	20.45	20.90	4.51	4.97	6.56	4.49	3.62	7.72	11.54	5.71	3.56	20/5.24	(8)	4.33	10.53	4.27	10.46
1943 Production	75,401	(16)	25/12,120	375,450	330,552	27/240,562	7,171	(28)	15,848	15,754	3,124	3/5,669	552,780	29/57,515	(30)	26/11,438	(8)	91,842	690,427	24,699	2,500,202
Average value per ton	$1.84	(16)	25/2.56	1.52	1.35	27/1.43	2.09	(28)	2.21	2.22	2.56	3/2.19	1.41	29/2.09	(30)	26/2.10	(8)	1.49	1.44	2.24	1.50
Average tons per man-day*	8.40	(16)	25/4.46	23.38	15.23	27/23.36	5.12	(28)	5.57	4.43	3.92	2.42	11.47	29/4.93	(30)	26/4.45	(8)	3.80	13.06	4.07	11.17
1944 Production	89,131	-	(5)	31/597,413	285,927	(5)	6,939	-	17,232	13,130	3,994	32/11,770	608,351	26,660	(33)	26/5,090	(8)	99,429	590,498	10,428	2,366,092
Average value per ton	$1.88	-	(5)	31/1.47	1.34	(5)	2.45	-	2.50	2.44	2.75	32/2.27	1.40	2.30	(33)	26/2.27	(8)	1.50	1.48	2.49	1.49
Average tons per man-day*	14.09	-	(5)	31/23.42	15.57	(5)	4.74	-	8.87	5.30	4.67	32/8.00	11.88	6.17	(33)	26/5.66	(8)	5.23	15.07	4.37	13.48
1945 Production	60,633	-	4,495	414,333	222,582	206,709	4,834	-	17,700	20,281	5,938	46,605	848,455	21,462	-	5,900	-	77,347	548,920	15,881	2,522,319
Average value per ton	$1.83	-	2.45	1.48	1.72	1.34	2.69	-	2.49	2.42	2.53	2.47	1.46	2.66	-	1.64	-	1.71	1.49	1.25	1.56
Average tons per man-day*	15.26	-	4.28	25.35	15.93	28.84	4.23	-	10.42	6.60	5.56	4.30	14.13	3.90	-	5.73	-	6.00	18.74	7.76	14.73
1946 Production	68,343	-	6,455	374,734	5,777	255,512	3,750	1,140	17,281	16,979	4,994	40,131	1,073,019	26,734	-	4,900	-	97,746	539,395	23,223	2,554,698
Average value per ton	$1.93	-	2.26	1.63	2.89	1.24	2.40	2.50	2.49	2.43	2.74	2.02	1.55	2.15	-	2.50	-	3.73	1.61	2.62	1.68
Average tons per man-day*	13.77	-	9.69	19.58	3.45	25.00	4.46	2.38	12.34	6.82	4.59	7.91	17.40	7.33	-	6.16	-	7.90	16.92	6.96	15.73
1947 Production	34/74,977	-	(22)	336,728	(22)	222,777	5,200	2,250	16,950	16,397	-	216,405	1,162,076	34,378	8,000	6,000	-	87,888	554,519	12,150	2,759,948
Average value per ton	34/$2.27	-	(22)	1.98	(22)	2.16	2.45	2.50	2.09	2.88	-	1.92	1.77	2.34	2.19	2.33	-	2.08	1.52	2.42	1.92
Average tons per man-day*	34/12.66	-	(22)	24.07	(22)	19.13	8.13	4.07	11.84	13.24	-	10.30	17.39	6.91	12.82	8.70	-	6.76	13.05	6.47	15.89
1948 Production	67,954	-	4,922	350,974	6,654	223,472	6,390	3,243	19,779	12,374	4,151	346,411	1,246,697	28,184	-	4,444	-	93,719	519,953	23,230	2,900,249
Average value per ton	$2.62	-	2.74	2.47	3.32	2.43	2.63	2.66	3.01	3.08	3.12	2.85	2.12	2.46	-	2.44	-	2.05	2.34	2.93	2.27
Average tons per man-day*	14.55	-	4.92	23.54	3.11	19.84	10.65	6.98	12.27	11.94	4.94	21.89	21.35	12.07	-	9.26	-	7.61	16.92	7.39	18.35
1949 Production	(28)	-	5,881	429,152	(28)	35/380,710	7,168	3,794	22,698	14,888	3,577	323,134	1,225,736	48,898	-	5,976	-	106,069	472,776	17,776	2,987,360
Average value per ton	(28)	-	$3.29	2.43	(28)	35/2.57	2.80	2.86	3.12	2.93	3.50	2.42	2.26	2.44	-	2.50	-	1.05	2.44	2.79	2.36
Average tons per man-day*	(28)	-	4.90	28.30	(28)	35/17.22	7.92	6.41	10.46	7.87	5.86	22.83	21.14	11.55	-	10.87	-	11.91	19.23	8.07	19.57
1950 Production	53,245	-	40,978	479,550	23,746	265,226	14,996	3,007	25,289	17,408	2,844	401,790	1,186,059	37,831	2,660	6,110	-	105,003	577,515	18,464	3,260,973
Average value per ton	$2.97	-	1.86	2.39	3.31	2.51	2.84	2.74	3.12	2.93	3.56	2.39	2.28	2.59	3.14	2.50	-	1.46	2.52	3.16	2.38
Average tons per man-day*	10.27	-	22.20	28.52	27.54	26.91	10.79	5.54	10.86	8.90	7.50	25.28	20.69	12.73	8.87	10.58	-	19.84	25.48	6.75	20.36
1951 Production	32,179	-	124,511	431,962	22,582	318,744	15,800	2,138	29,143	17,333	3,273	328,169	1,174,213	33,894	7,668	6,700	-	119,961	540,376	16,714	3,224,327
Average value per ton	$3.28	-	1.78	2.49	3.14	2.29	2.83	2.79	3.09	2.90	3.75	2.45	2.29	2.54	3.98	2.50	-	2.53	2.61	3.38	2.41
Average tons per man-day*	14.29	-	41.67	23.93	15.08	20.91	14.38	7.75	15.44	9.79	3.96	19.84	20.02	10.22	11.13	21.40	-	12.24	18.93	6.40	20.26
1952 Production	22,114	-	148,936	440,907	20,096	297,840	10,012	1,990	20,954	15,693	1,190	289,200	1,054,777	37,192	1,905	6,280	-	75,779	522,628	17,776	2,983,752
Average value per ton	$3.31	-	1.64	2.33	3.35	2.37	2.75	2.73	3.13	2.87	4.00	2.49	2.33	2.55	4.05	2.50	-	2.61	2.49	3.38	2.37
Average tons per man-day*	14.14	-	37.42	31.46	22.11	17.52	10.12	5.23	12.24	10.47	5.95	19.92	21.97	13.20	10.03	19.01	-	12.24	20.04	6.66	21.56

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Footnotes to Table 25.

1. Included under Golden Valley County.
2. Includes Billings, Golden Valley, and Oliver Counties.
3. Includes Billings, Golden Valley, and McKenzie Counties.
4. Includes Burke and Divide Counties.
5. Included under Burke County.
6. Includes Billings and Golden Valley Counties.
7. Includes Golden Valley and McKenzie Counties.
8. Included under Oliver County.
9. Includes Golden Valley, McKenzie, and Oliver Counties.
10. Includes Dunn, Golden Valley, and Oliver Counties.
11. Included under Dunn County.
12. Includes Dunn and Golden Valley Counties.
13. Includes Dunn, Golden Valley, McKenzie, and Oliver Counties.
14. Included under McKenzie County.
15. Includes Billings and McKenzie Counties.
16. Included under Bowman County.
17. Includes Billings, Bowman, and Slope Counties.
18. Includes Billings, Golden Valley, and Slope Counties.
19. Includes Billings, Dunn, and Slope Counties.
20. Includes Billings, Bowman, Dunn, and Slope Counties.
21. Includes Adams and Billings Counties.
22. Included under Adams County.
23. Included under Stark County.
24. Includes Stark and Slope Counties.
25. Includes Billings and Bowman Counties.
26. Includes Oliver and Slope Counties.
27. Includes Divide and Golden Valley Counties.
28. Included under Divide County.
29. Includes Morton and Mountrail Counties.
30. Included under Morton County.
31. Includes Bowman, Burke, and Divide Counties.
32. Includes McLean and Mountrail Counties.
33. Included under McLean County.
34. Includes Adams, Bowman, and Burleigh Counties.
35. Includes Adams, Burleigh, and Divide Counties.

N.A. Not available.

* High averages represent a preponderance of stripping.

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With respect to trends in the availability of the respective sources of energy in North Dakota, table 26 shows that from 1937 through 1946 the proportion of natural gas was small and that there was no power from hydro. Although comparable data for subsequent years are not available because of the lack of coal-distribution data, other sources indicate that from 1946 to 1951 annual consumption of natural gas in North Dakota increased less than 900 M cubic feet. The declining demand for coal is the result of increased availability and use of fuel oil. The future of North Dakota lignite will depend to a large extent on the availability of oil and natural gas, both in North Dakota and in adjacent areas which may be looked upon as potential lignite markets. Relative price levels of the respective fuels will be the principal determinant in the industrial market and to some extent with respect to domestic consumption, although the factor of convenience and general desirability for oil and natural gas will be a strong factor in domestic consumption. As indicated in table 27, domestic consumption of North Dakota lignite stayed ahead of industrial use until 1946 when industrial consumption moved ahead. With the increased production of thermal power in the area, together with the steady rise in the availability of competitive fuels, industrial markets probably hold the key to any appreciable advancement in the production of North Dakota lignite.

TABLE 26. - Percentage of approximate total B.t.u. equivalent consumption contributed by the several mineral fuels and waterpower in North Dakota during 1937 and 1944-46[1/]

	Bituminous coal and lignite[2/]	Natural gas	Fuel oil	Hydroelectric power[3/]
1937.....	88	4	8	0
1944.....	82	5	13	0
1945.....	75	5	20	0
1946.....	73	5	22	0

1/ These are the only years for which basic data on lignite distribution are available, as a base for these comparisons.
2/ Excludes railroad fuel. 3/ At prevailing central station equivalent.

With respect to potentially new markets for North Dakota lignite, tables 27 and 28 have been prepared to show something of the distribution of bituminous coal and lignite into States that might be considered part of those potential markets, that is, Iowa, Minnesota, Nebraska, South Dakota, and Wisconsin. Table 28 shows also the coal-producing districts from which the tonnages moved into these States during the limited period for which bituminous-coal distribution data are available.[2/] It is significant to note that, although the largest tonnages that moved into these States came from Illinois (District 10[3/]), substantial tonnages came by rail and water transportation from western Pennsylvania, southern West Virginia, and eastern Kentucky.

2/ These data were collected and published by the Bureau of Mines in cooperation with the Solid Fuels Administration for War. Similar data have not been collected since 1946.
3/ See Mineral Market Report 2102, p. 10, for geographical definition of the respective coal-producing districts.

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TABLE 27.--Distribution of North and South Dakota lignite by method of movement, State of destination, and consumer use during calendar years 1944-46 1/
(In net tons of 2,000 pounds)

Method of movement, State of destination, and consumer use	1944	1945	1946
All-rail movement:			
Minnesota:	92,718	140,036	145,780
Industrial	48,329	86,835	89,024
Retail yards	44,389	53,201	56,756
Montana:	3,534	2,878	--
Industrial	--	110	--
Retail yards	3,534	2,768	--
North Dakota:	1,542,751	1,662,884	1,745,276
Industrial	701,728	771,177	842,574
Retail yards	841,023	891,707	902,702
South Dakota:	124,238	119,075	148,359
Industrial	90,187	93,342	121,012
Retail yards	34,051	25,733	27,347
Unknown State:	41	--	1,358
Industrial	--	--	174
Retail yards	41	---	1,184
Total all States:	1,763,282	1,924,873	2,040,773
Industrial	840,244	951,464	1,052,784
Retail yards	923,038	973,409	987,989
Railroad fuel	117,637	119,444	144,384
Truck shipments reported 2/	116,511	96,619	130,714
Lignite used at mines 3/	122,850	115,760	83,861
Net change in inventory	-457	-105	‡2,639
Total production reported	2,119,823	2,256,591	2,402,371
Estimated truck production Not reported 4/	421,004	332,746	258,183
Grand total	2,540,827	2,589,337	2,660,554

1/ Distribution data were not shown separately for these two States.
2/ Includes only mines with an average daily capacity of 50 tons or more and all mines with rail connections that reported on Form S.F.A. No. 56.
3/ Includes lignite used to produce lignite and lignite used by mine employees.
4/ Represents total truck tonnage reported for the Calendar Years 1944-46 less tonnages shown in Truck Shipments Reported. These tonnages were those produced at small truck mines not required to report on Form S.F.A. No. 56.

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TABLE 28. - Distribution of bituminous coal and lignite during the year ended June 30, 1944, to selected States of destination by districts of origin1/2/

District of origin3/	Iowa	Minnesota	Nebraska	North Dakota	South Dakota	Wisconsin	Total
1	1,892	10,883	1,491	534	737	78,229	93,766
2	1,708	65,636	-	-	-	406,985	474,329
3	12,314	4,565	-	2,464	-	107,530	126,873
4	4,184	12,598	-	-	633	13,495	30,910
6	-	-	-	-	-	4,849	4,849
7	67,496	386,026	440	-	7,816	1,188,341	1,650,119
8	928,223	243,430	5,513	-	3,066	1,535,625	2,715,857
9	311,925	45,520	9,023	1,234	16,799	169,245	553,746
10	4,087,496	979,700	404,231	634	121,174	2,282,805	7,876,040
11	545,969	148,113	38,975	-	6,506	957,893	1,697,456
12	739,637	290	693	-	-	-	740,620
14	104,779	55,121	214,439	-	30,515	-	404,854
15	230,057	12,028	912,888	312	31,926	-	1,187,211
16	1,990	-	44,076	-	330	-	46,396
17	9,899	565	511,809	-	54,135	-	576,408
19	8,765	931	275,226	7,479	80,692	-	373,093
20	-	-	4,862	-	1,824	-	6,686
21	-	87,000	-	1,589,000	123,000	-	1,799,000
22	325	9,384	-	38,304	95,258	-	143,271
Great Lakes, ex-dock4/	128,000	4,234,000	20,000	260,000	443,000	7,028,000	12,113,000
Total	7,184,659	6,295,790	2,443,666	1,899,961	1,017,411	13,772,997	32,614,484

1/ Excludes railroad fuel. 2/ All rail, river, ex-river, and Great Lakes interport shipments, by district of origin.

3/ See Mineral Market Rept. 2032, p. 10, column 1, for definition of districts.

4/ These are the tonnages of bituminous coal shipped off upper Great Lakes commercial docks, the districts of origin of which are not available.

As reserves of high-quality bituminous coal are almost unlimited, and regardless of any possible future decline in the availability of oil and natural gas in these potentially new market areas (which would be contrary to present expectations), the prospects for North Dakota lignite moving into these new markets will be rather restricted unless the problems of quality of product, efficiency in utilization and transportation costs are solved.

The following publications, which contain additional statistical data pertaining to North Dakota lignite, may be obtained from the Bureau of Mines on application:

a. Mineral Market Report 2102, Bituminous Coal and Lignite in 1951. This report includes additional data with respect to North Dakota not referred to above, together with comprehensive data regarding bituminous coal, which might be of value for comparative purposes. The report covering 1952 will be available in November.

b. Mineral Market Report 1592, Bituminous-Coal Distribution, Calendar Year 1946. Reports for other years no longer are available.

c. Weekly Coal Report 1846, pp. 6-9 include the latest tables on relative rates of growth of coal, oil, natural gas, and water power.

In addition, those who are interested in the data for previous years are referred to the chapters on bituminous coal and lignite in the Minerals Yearbook and to the volumes on Mineral Resources of the United States for years before 1932.

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